NATIONAL BUREAU OF STANDARDS REPORT

7399

EVALUATION OF RESISTANCE STRAIN GAGES
AT ELEVATED TEMPERATURES

Progress Report No. 13

by

R. L. Bloss, J. T. Trumbo, C. H. Melton
and J. S. Steel

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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Engineering Mechanics Section
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Technical Report

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FOREWORD

In recent years the use of structures at elevated temperatures has increased greatly. If the safe design and efficient use of structural materials are to be assured, a knowledge of the properties of materials and of structural configurations is essential. In determining these properties, the measurement of strains and deformations is important. Strain gages to measure these quantitities must be capable of operating satisfactorily over a wide temperature range.

In order to determine the characteristics of strain gages that are available for use at elevated temperatures, the Department of the Navy and the Department of the Air Force have sponsored a program for the evaluation of these gages. Results obtained from only one gage type are given in this report so that performance information may be made available without undue delay. Results obtained from other gage types have been presented in earlier reports of this series.

There is a continuing effort on the part of manufacturers and research organizations to develop improved strain gages for use at elevated temperatures. Therefore the results given in this report would not necessarily show the performance of similar gages which may differ in characteristics due to differences in materials, treatments, or methods of fabrication.

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Synopsis

Type FNO-50-12E resistance strain gages, manufactured by the Baldwin-Lima-Hamilton Corporation, were evaluated at elevated temperatures. The results of the evaluation tests indicate that the gage factor at 75° F is lower than the value given by the manufacturer; that the gage factor decreases in a regular, repeatable manner with increasing temperature; that the gages are able to sustain strains of 0.004 or more without failure at 75° and 600° F; that the drift is low at temperatures as high as 800° F; that the temperature sensitivity can be made low and repeatable by the proper choice of circuit constants if the temperature does not exceed 850° F; that the gage response is repeatable when subjected to transient heating conditions; and that the gage response is not greatly affected by heating rate.

1. INTRODUCTION

In the continuing evaluation of resistance strain gages designed for use at elevated temperatures, gages manufactured by the Baldwin-Lima-Hamilton Corporation were subjected to tests. The gages tested were type FNO-50-12E. These gages were subjected to tests to determine the following characteristics:

1. Gage factor at about 75° F,
2. Variation of gage factor with increasing temperature,
3. Response of the gages when subjected to large strains,
4. Relative change of gage resistance with time at constant temperatures,
5. Resistance-temperature relationship and how it is affected by circuit constants,

6. Behavior when subjected to various heating rates, and

7. Resistance between the gage and the test strip as a function of temperature.

The results of previous evaluations of other gage types are given in references 1 through 11.

2. GAGE DESCRIPTION

The gages reported on herein are type FNO-50-12E purchased from the Baldwin-Lima-Hamilton Corporation through their local sales representative. They are described in the manufacturer's Bulletin No. 4321. Figure 1 is a drawing of a gage as received. Figure 2 is a schematic diagram of a gage connected as part of a bridge circuit. A gage consists of an "active" element of Nichrome foil having a resistance of about 120 ohms and a "compensating" element of platinum wire having a resistance of about 3.5 ohms. Because of the different values of temperature coefficient of resistance, temperature coefficient of expansion, gage factor, and resistance of the active and compensating elements, the temperature sensitivity of the entire gage can be adjusted over a wide range by proper selection of the resistor R_B (Fig. 2). Analysis of the circuit shows that the lowest temperature sensitivity will be obtained when

$$R_B = \left[\frac{R_T}{R_G}\right]\left[\frac{\alpha_T + K_T(\beta_S - \beta_T)}{\alpha_G + K_G(\beta_S - \beta_G)}\right][R_G + R_{LG}] - [R_T + R_{LT}] \tag{1}$$

where

α = temperature coefficient of resistance

K = strain sensitivity

β = temperature coefficient of linear expansion

and the subscripts T, G, S, and L refer to the compensating element, active element, specimen material, and leads respectively.

Allen P-1 cement, also purchased from the Baldwin-Lima-Hamilton Corporation, was used to attach the gages to types 302 and 303 stainless steel and Inconel test strips. In nearly all cases the thicker cement coatings over the gage leads had cracks after the final curing. In a few cases very fine cracks were found over the grid area. The gages were installed in accordance with instructions received with the gages except that (1) just prior to application of the cement precoat the test strip was cleaned by scrubbing with cement on a tissue and rinsing

with distilled water, and (2) the heating of the test strip from 200° to 600° F for curing purposes was accomplished in about one and one-half hours instead of the recommended two hours. The installation procedures are described in the appendix to this report.

3. TEST EQUIPMENT AND METHODS

The equipment and methods used for all evaluation tests except the determination of the resistance between the gage and the test strip have been described in references 5, 8, 12, 13, and 14.

The circuit used for measuring the "leakage resistance" is shown in Figure 3. The gage and test strip are connected into the circuit electrically so that the resistance between them (R_L) is in series with a d-c power source, an X-Y recorder having an input resistance (R_R) of two megohms, and an external resistor (R_M) of two megohms. The signal driving the recorder is the voltage generated across the recorder resistance,

$$V_R = \frac{ER_R}{R_L + R_M + R_R} \tag{2}$$

Since the values of R_M and R_R are known, the leakage resistance can be determined as

$$R_L = \frac{ER_R}{V_R} - (R_M + R_R) \tag{3}$$

where E may be any convenient value.

The value of V_R was recorded with the temperature of the test strip increasing at about 10° F per second. The input voltage, E, was adjusted so that full scale record was obtained as R_L varied from 0 to ∞ and the scale was marked in terms of R_L as computed from equation (3).

4. RESULTS

The number of gages subjected to the various tests and the voltages applied to the test circuits are shown in Table 1. The heating rates of transient heating tests are given in Table 2. The results of the evaluation tests are given in Table 3 and Figures 4 through 33.

4.1 Gage Factor

Gage factor values were obtained at about 75° F from four gages for a maximum strain of about 0.001 in tension and compression. These values are given in Table 3 where

K_u = gage factor for increasing load,

K_d = gage factor for decreasing load, and

$\bar{K}$ = average of K_u and K_d.

All gage factor values at 75° F were lower than the manufacturer's nominal value, but, to two significant figures, all values were within the stated range, 2.2 ± 0.1. Gages 2.4-A_1 and A_3 were tested in tension before being tested in compression. Gages 2.4-A_2 and A_4 were tested in compression before being tested in tension.

Figure 4 shows the differences between the experimentally determined gage factor values and the manufacturer's nominal value expressed as a percentage of the nominal value. Departure from the diagonal line indicates a difference between gage factor values for tensile and compressive loading. Values for the first loading cycle, shown as solid symbols, were generally somewhat different than values from subsequent tests.

Figures 5 and 6 show the departure from linearity of the gage response and the zero shift for the first and third loading cycles. The maximum strain was about 0.001. Open symbols indicate an increasing load and solid symbols are for decreasing load. No corrections were applied for temperature fluctuations. Examination of the data and figures indicates that the gage response to strain is nearly linear and that strains computed using the nominal gage factor value, 2.2, did not differ from actual values by as much as 50 microinches per inch.

4.2 Variation of Gage Factor With Temperature

The variations of gage factor with increasing temperature are shown in Figures 7 through 10. Each curve of Figures 7 through 9 represents the average change of gage factor of two gages that were mounted on opposite

sides of a cantilever beam and connected as adjacent arms of a bridge circuit. Figure 10 shows the average of all runs for each set of two gages and the extreme values of all tests. These figures show the repeatability from gage to gage and among tests of the same gages. The gage factor decreases about 1.7 percent for each one hundred degrees Fahrenheit increase of temperature between 75° and 800° F. The rate of gage factor decrease becomes less at temperatures above 800° F.

4.3 Large Strains

Four gages were subjected to tensile strains greater than those used for the determination of gage factor. The results are shown in Figures 11 and 12. In order to determine the strain indicated by the gage, $\epsilon_{ind} = \frac{\Delta R}{KR}$, the value of K at 75° F was taken as the grand average of the values determined in the gage factor tests at room temperature. For the tests at 600° F, the room temperature gage factor value was adjusted by the average amount found during the variation of gage factor with temperature tests.

The behavior of the gages at the larger strains could be caused by a failure of the bond between the gage and the test specimen or by a rapid increase in the resistance of the compensating arm. Since visual examination of the specimens after completion of the tests did not indicate a loosening of the bond, it is supposed that the large errors were caused by the compensating element.

4.4 Drift

Records of relative change of gage resistance with time for three gages at various test temperatures are shown in Figures 13 through 19. These results were obtained after heating the gage installation at about 10° F per second from room temperature or the next lower test temperature. Recording was started one minute after the desired test temperature was reached. The second test series was made after the gages had been tested once at each test temperature up to 1200° F. The temperature fluctuations during the tests did not exceed ± 3° F except during the first test series of gage 2.4-D_2 at 1200° F (+2, -4° F). The data was not corrected for temperature fluctuations.

The drift was generally less than 0.001 during the thirty minute tests except at 900° and 1000° F and during the first test series at 1200° F. It should be noted that the drifts occuring during the second test series at 900° F were greater than those occuring during the first test series. The occurance of both positive and negative drifts at 1000° F should also be noted.

4.5 Temperature Sensitivity

Temperature coefficient values (relative change of gage resistance per unit temperature change) for three gages mounted on type 302 stainless steel are shown in Figures 20 and 21. Each point was determined as the slope of a line drawn tangent to a curve of relative change of gage resistance versus temperature recorded while the test strip temperature was increasing at about 10° F per second. Figure 20 shows values for two tests to a maximum temperature of 850° F. The value of R_B was computed from values of R_G, R_T, and R_L (Figure 2) measured prior to gage installation, constants furnished by the manufacturer, and handbook values of coefficients of linear expansion of materials. The values obtained from each gage were repeatable for the two tests. Values for two of the gages, 2.4-T_1 and T_3, were in close agreement. The appreciably different values obtained for gage 2.4-T_2 show the desirability of establishing the value of R_B experimentally whenever possible.

Figure 21 shows the results obtained from the same gages, using the same circuit constants, when the tests were carried to 1200° F. Run 3 for gage 2.4-T_3 is not shown as the maximum temperature was 850° F. This figure shows that exposure to this higher temperature changes the characteristics of the gages. It should be noted that the manufacturer recommends these gages for use at temperatures up to 850° F.

Figures 22 and 23 show how the sensitivity of the gages can be changed by changing the value of R_B. The gages for these tests were mounted on type 302 stainless steel and Inconel. The effect of the coefficient of linear expansion of the base material on the value of R_B required for good compensation can also be seen since the resistance values for gages 2.4-T_4 and T_5 were very nearly the same.

4.6 Transient Heating

The change of gage resistance of three gages was measured as the test strips to which they were attached were subjected to radiant heating at rates of 2° F per second to about 90° F per second. The strips and gage areas were then painted black and the tests were repeated at heating rates of 50° F per second to 130° F per second. The results of some of these tests are given in Figures 24 through 30. Gage No. 2.4-R_1 could not be tested after painting because of the low leakage resistance between the gage and the test strip. The heating rates for all test runs are shown in Table 2.

Figures 29 and 30 show the effect of history, heating rate, and painting on the response of the gages. The agreement between the results of runs 2 and 18 indicate that the intervening history had little effect upon the gage response. The results of run 1 were, however, significantly different from results of subsequent test runs. The effect of various heating rates for the tests of unpainted gages was small, and the effect was qualitatively the same for both gages, 2.4-R_2 and 2.4-R_3. Painting of the gage area and test strip changed the response of the gages significantly and increased the effect of heating rate. The effect was qualitatively the same for both gages.

4.7 Leakage Resistance

The resistance values between the gage and test strip, as determined with the circuit of Figure 3, are shown in Figures 31 through 33. Three tests were made to maximum temperature of about 850° F followed by three tests to about 1200° F. The gage installations had been previously cured at 600° F. These figures show the effect of temperature and history on the insulating properties of the cement. The values shown can be considered as only a qualitative indication of the insulating property of the cement since ceramic cements would not be expected to follow Ohm's law (Reference 15).

5. CONCLUSIONS

For gages of this type, the data obtained from the evaluation tests covered by this report indicate that:

(1) The gage factor values determined at strains up to 0.001 at 75° F were consistently lower than the value given by the manufacturer. The average of all gage factor values obtained was about 4 percent lower than the nominal value.

(2) The gage resistance is a nearly linear function of strain for strains up to 0.001.

(3) The gage factor decreases in a nearly linear manner with increasing temperature up to 800° F. The decrease is about 12 percent between 75° and 800° F.

(4) The gages were able to sustain strains greater than 0.004 before gage failure at 75° and 600° F. Errors exceeding 10 percent were not observed until strains of 0.003 or more.

(5) The relative change of gage resistance with time at nearly constant temperature was generally less than 0.001 in thirty minutes except for tests at 900°, 1000° and 1200° F. The effect of gage history on the drift varied from gage to gage, expecially at 800° and 1000° F.

(6) The temperature sensitivity of a gage is a repeatable function of temperature if the test temperature does not exceed 850° F, the maximum temperature recommended by the manufacturer. If the gage is heated to 1200° F the temperature sensitivity is changed significantly.

(7) By adjusting the resistor in series with the compensating element, the temperature sensitivity can be varied over a wide range. It was possible to find a value for this resistor to give a low temperature sensitivity for temperatures up to 850° F.

(8) The gages are operative when attached to stainless steel test strips that are heated by radiant heat lamps at rates as high as 130° F per second. Painting the gage area to increase the emissivity changes the response of the gage and increases the effect of heating rate. Before being painted, the gage response was not affected by the thermal history to which the gages were subjected.

(9) The resistance between the gage and the test strip decreases rapidly at higher temperatures. This resistance is a function of the thermal history of the gage.

Washington, D. C.
December 1961

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APPENDIX

The type FNO-50-12E gages tested for this report were installed on stainless steel (type 302 and 303) and Inconel in the following manner.

A. Cement Preparation

1. Allen P-1 cement, procured from the Baldwin-Lima-Hamilton Corporation, was mixed in the proportion of two parts powder to one part liquid by volume.

2. A few hours were allowed to elapse before the cement was used.

B. Surface Preparation

1. The test specimens were cleaned with toluol and then acetone to remove petroleum products.

2. The surface was roughened, recleaned with acetone, scrubbed with cement, and rinsed with distilled water.

3. A thin coating of cement, about 0.001 inch thick, was applied to an area larger than would be occupied by the gage. The precoat was air dried for 30 minutes and then cured for one hour at 220° F followed by one hour at 600° F.

C. Gage Preparation

1. A one-inch piece of Nichrome V ribbon was formed into a "fish mouth" by folding one end of the ribbon back on itself, welding the free end to itself to form a small loop, and cutting the end of the loop. The "fish mouth" thus formed was sandwiched over a gage tab and spot welded to it.

2. The glass tape on both sides of the gage adjacent to the vinyl "fingers" was clipped with a small pair of straight blade scissors and the gage removed from the envelope.

3. The gage was placed bottom side up (tape down) on a flat surface, and the leads were gently flattened so that they would lie flat.

4. The cement was stirred with a clean brush; the excess cement was removed; and the grid and gage tabs were stroked parallel to the strands, moving in one direction only, until the surface was wet.

5. The gage was then removed to a dry area by pulling on the leads and "dragging" the gage.

D. Gage Installation

1. The surface of the precoat was prewetted by applying a heavy coat of cement and then removing the excess with a piece of gauze.

2. A thin coat of cement was applied to the precoat and the gage was placed into the cement with the glass tape up.

3. A thin coat of cement was brushed over the exposed gage strands. A thicker coat was applied over the leads and tabs and the installation was allowed to air dry for about 10 minutes.

4. Another thin coat of cement was applied as before and allowed to dry.

5. Using a cotton swab, the glass tape was soaked in alcohol for a few minutes and then removed with a pair of tweezers.

6. The exposed area was cleaned of any remaining adhesive using a cotton swab and alcohol.

7. The exposed surface of the gage was wet with cement and allowed to dry for about 10 minutes.

8. A second coat of cement was applied and allowed to dry as before. A heat lamp was used to dry the installation thoroughly.

9. A third coat of cement was then applied over the entire gage, blending in the transverse "joining" marks.

10. The final coat was allowed to air dry and then was cured according to the following schedule:

a. The temperature of the installation was slowly raised to 200° F and held for 2 hours.

b. The temperature was raised to 600° F in about 1 1/2 hours and held for one hour.

c. The specimen was allowed to cool slowly.

11. Leads were attached to the gage installation.

Table 1 - Number of Gages Tested and Circuit Voltage

Type of Test	No. of gages tested	Electrical input to circuit
		volts
Gage factor determination	4	3
Variation of gage factor with temperature	6	6
High strain	4	3*
Resistance instability (drift)	3	5
Temperature sensitivity	5	5
Transient heating	3	5
Leakage resistance	3	10

*ac (1000 cps); all other dc.

Table 2 - Heating Rates for Transient Heating Tests

Run No.	Nominal heating rate	Measured average heating rate Gage $2.4\text{-}R_1$	Gage $2.4\text{-}R_2$	Gage $2.4\text{-}R_3$	Run No.	Nominal heating rate	Measured average heating rate Gage $2.4\text{-}R_1$	Gage $2.4\text{-}R_2$	Gage $2.4\text{-}R_3$
	°F/sec	°F/sec	°F/sec	°F/sec		°F/sec	°F/sec	°F/sec	°F/sec
1	50	48	50	50	16	2	2.0	2.0	2.0
2	50	49	51	(a)	17	2	2.0	2.0	2.0
3	50	48	51	50	18	50	49	50	50
4	50	48	50	50	19	50	50	50	50
5	50	48	51	50	20	50	50	50	50
6	(b)	85	90	88	21(c)	50	(d)	50	49
7	(b)	85	90	88	22(c)	50	--	(a)	50
8	(b)	85	90	88	23(c)	50	--	50	50
9	25	24	24	24	24(c)	100	--	100	100
10	25	23	24	24	25(c)	100	--	96	97
11	25	23	24	24	26(c)	100	--	97	96
12	10	9.8	9.9	10.0	27(c)	(b)	--	130	132
13	10	9.9	10.0	10.0	28(c)	(b)	--	121	130
14	10	9.9	10.0	10.0	29(c)	(b)	--	130	127
15	2	2.0	2.0	2.0					

(a) Heating rate was not determined.
(b) Maximum heating rate obtainable (not linear)
(c) Gage area and test strip painted black
(d) Leakage resistance became very low when painted. Tests of this gage were discontinued.

Table 3 - Gage Factor Values at 75° F

Gage No.	Run No.	Gage Factor Values					
		Tension			Compression		
		K_u	K_d	$\bar{K}$	K_u	K_d	$\bar{K}$
$2.4\text{-}A_1$	1	2.124	2.111	2.117	2.154	2.116	2.135
	2	2.114	2.110	2.112	2.116	2.107	2.111
	3	2.123	2.114	2.118	2.114	2.112	2.113
	Average			2.116			2.120
$2.4\text{-}A_2$	1	2.189	2.146	2.168	2.132	2.081	2.106
	2	2.150	2.146	2.148	2.093	2.098	2.096
	3	2.151	2.154	2.152	2.093	2.096	2.094
	Average			2.156			2.099
$2.4\text{-}A_3$	1	2.068	2.085	2.077	2.127	2.121	2.124
	2	2.073	2.083	2.078	2.117	2.121	2.119
	3	2.080	2.085	2.082	2.114	2.113	2.114
	Average			2.079			2.119
$2.4\text{-}A_4$	1	2.075	2.069	2.072	2.146	2.089	2.118
	2	2.093	2.091	2.092	2.094	2.085	2.089
	3	2.098	2.091	2.094	2.099	2.081	2.090
	Average			2.086			2.099
	Grand Average			2.109			2.109

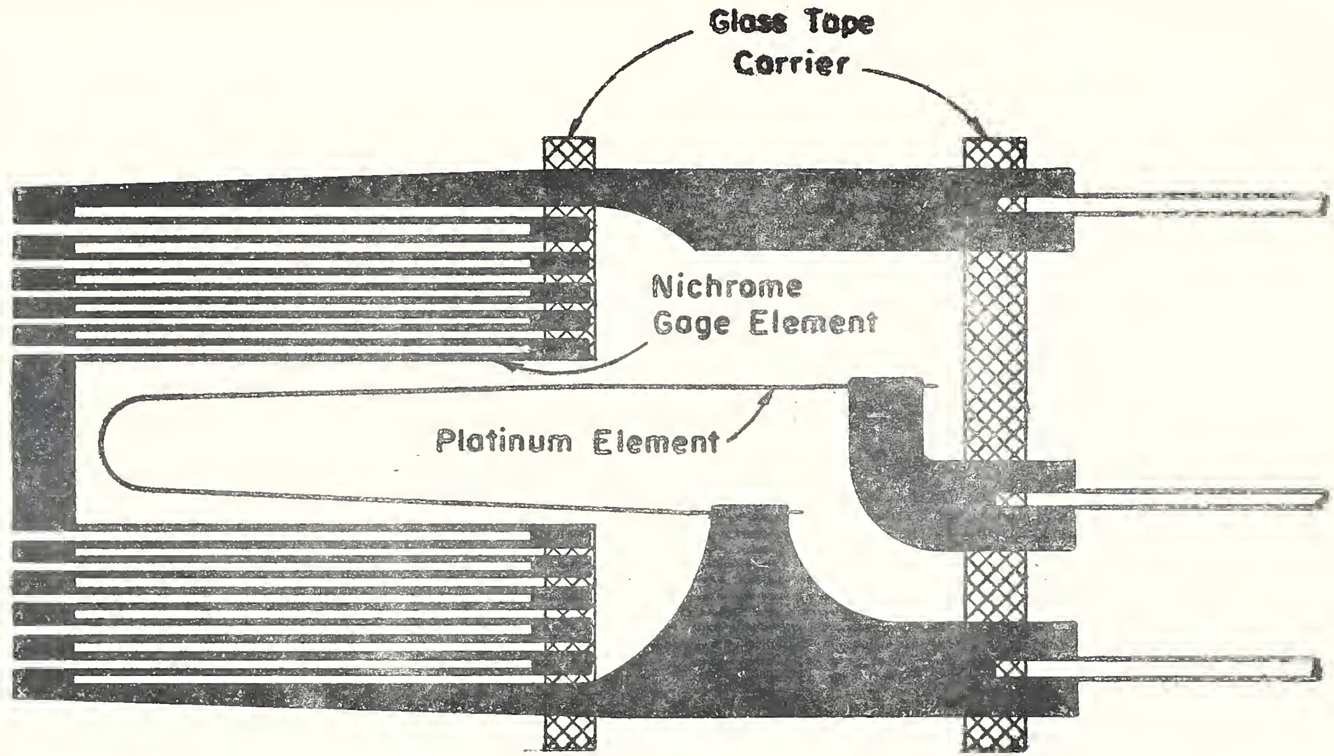


Fig. 1 Gage configuration.

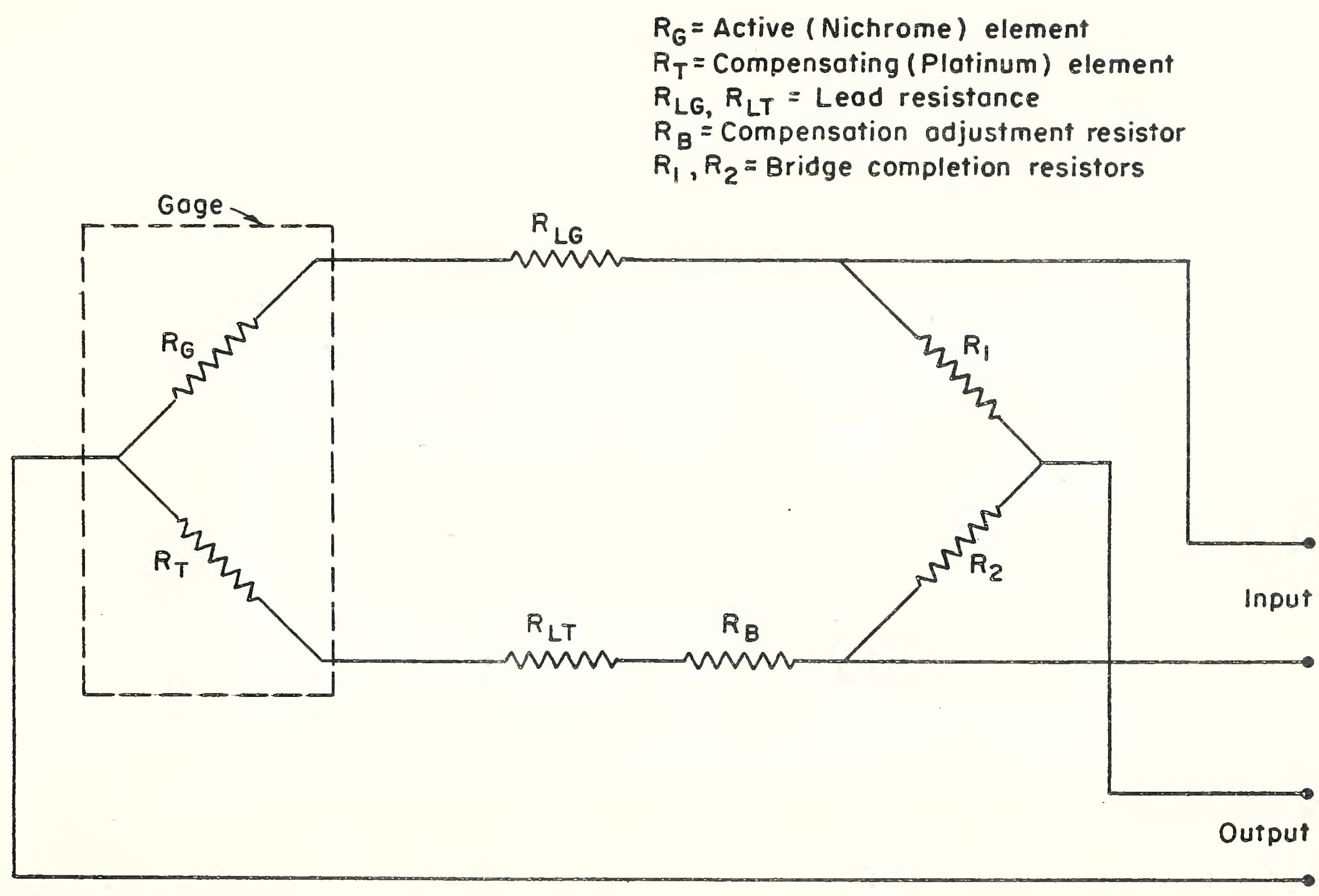
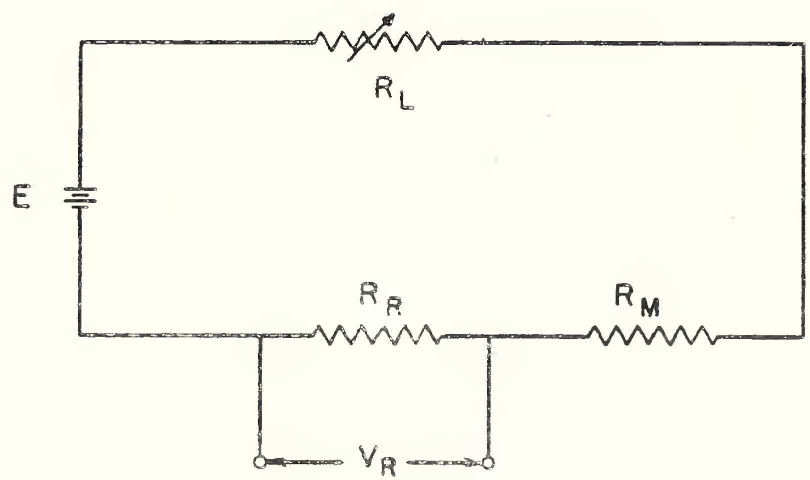


Fig. 2 Strain gage circuit.



R_L = Leakage resistance

R_R = Recorder resistance

R_M = External resistance

E = Applied voltage

V_R = Signal to recorder

Fig. 3 Circuit for measuring leakage resistance.

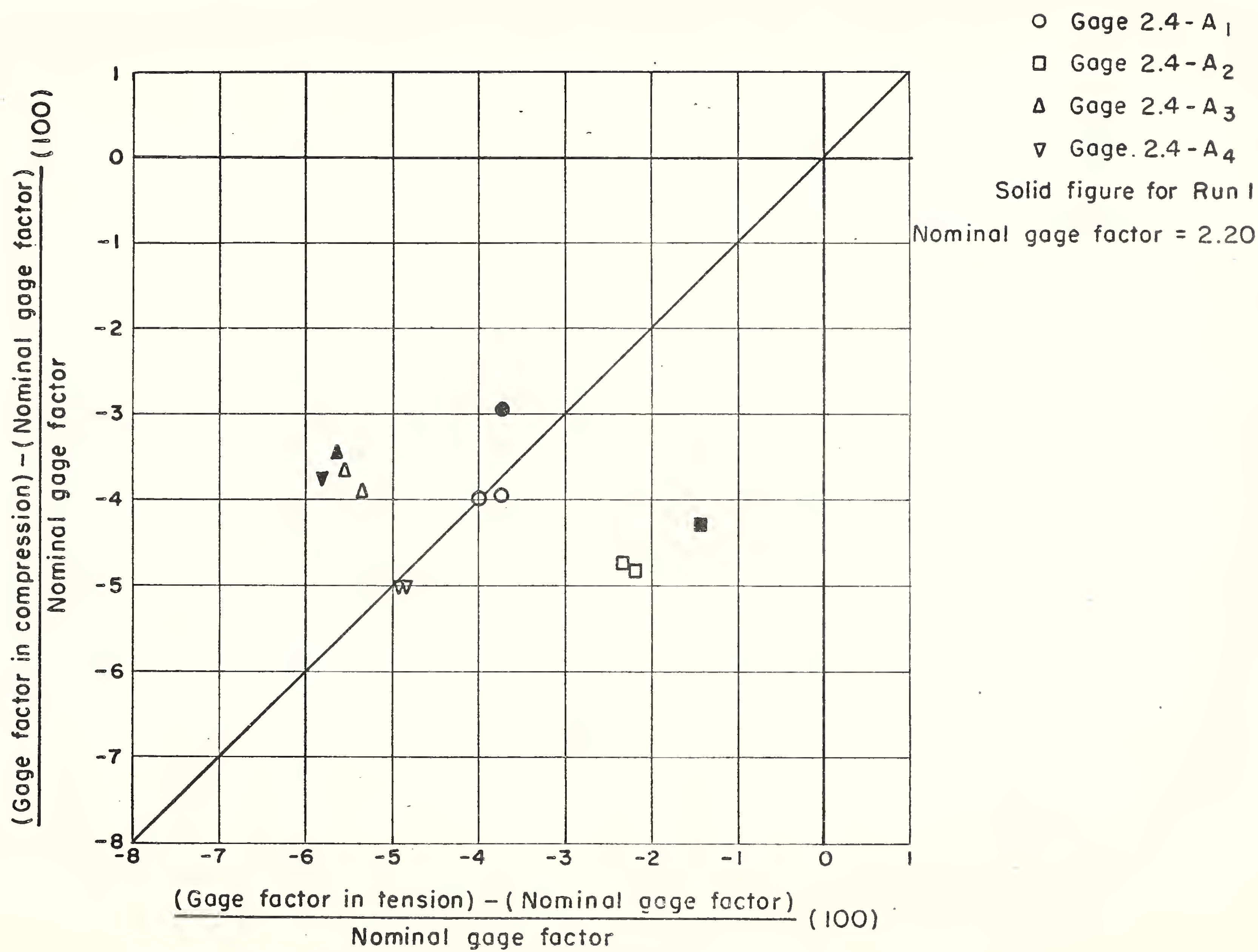


Fig. 4 Gage factor deviation at 75° F.

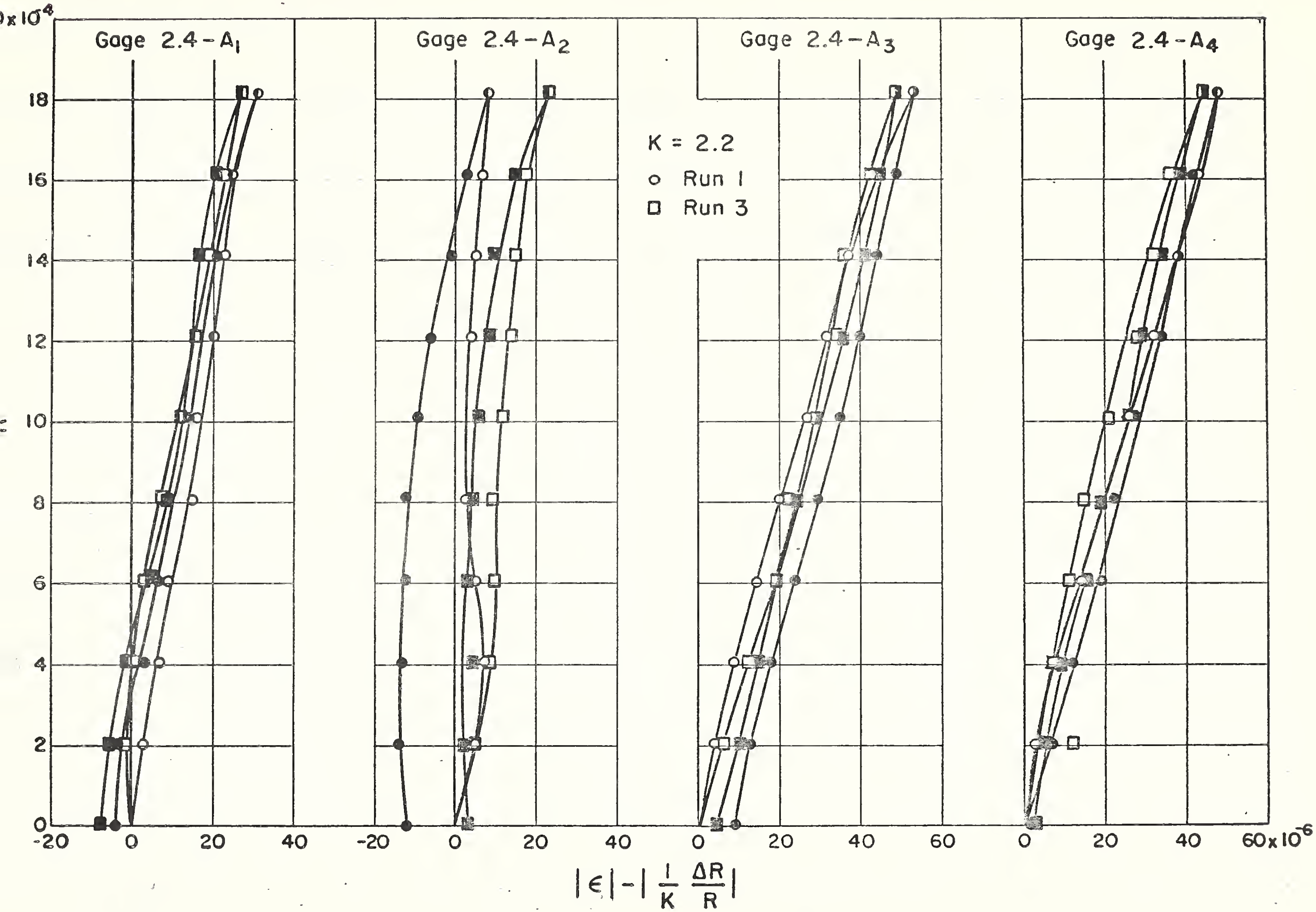


Fig. 5 Strain deviation for tension loading at 75°F

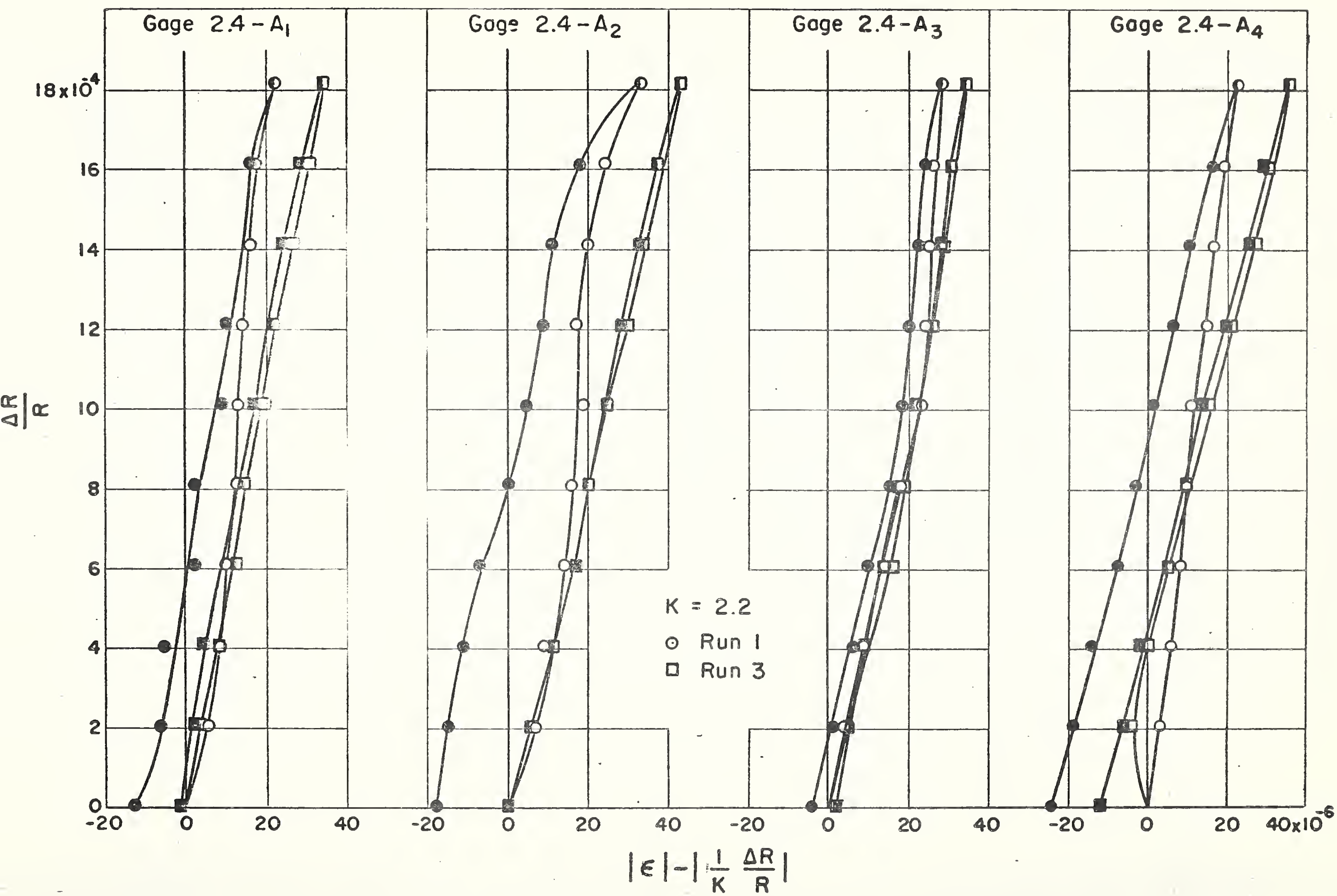


Fig. 6 Strain deviation for compression loading at 75° F.

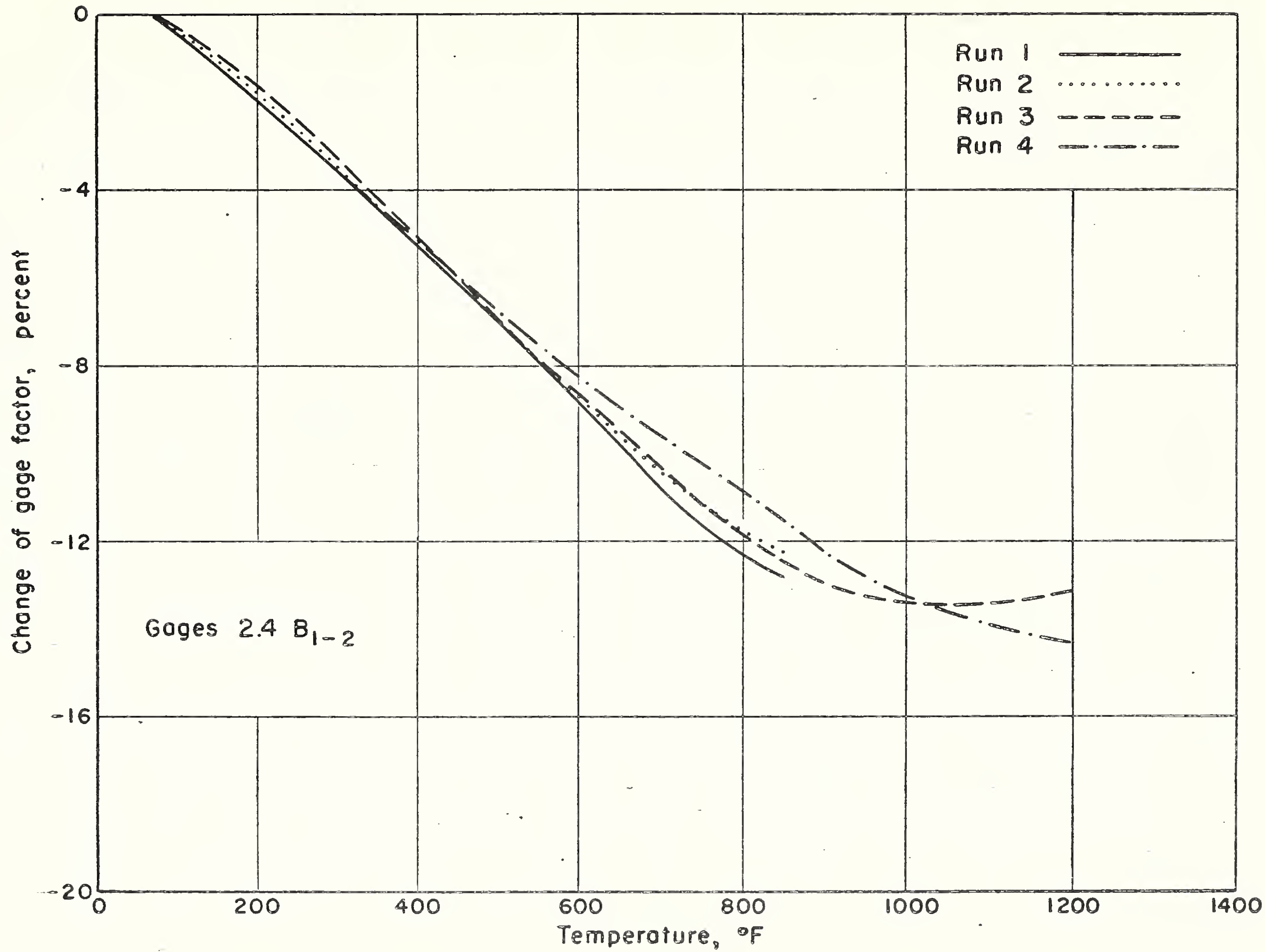


Fig. 7 Variation of gage factor with temperature.

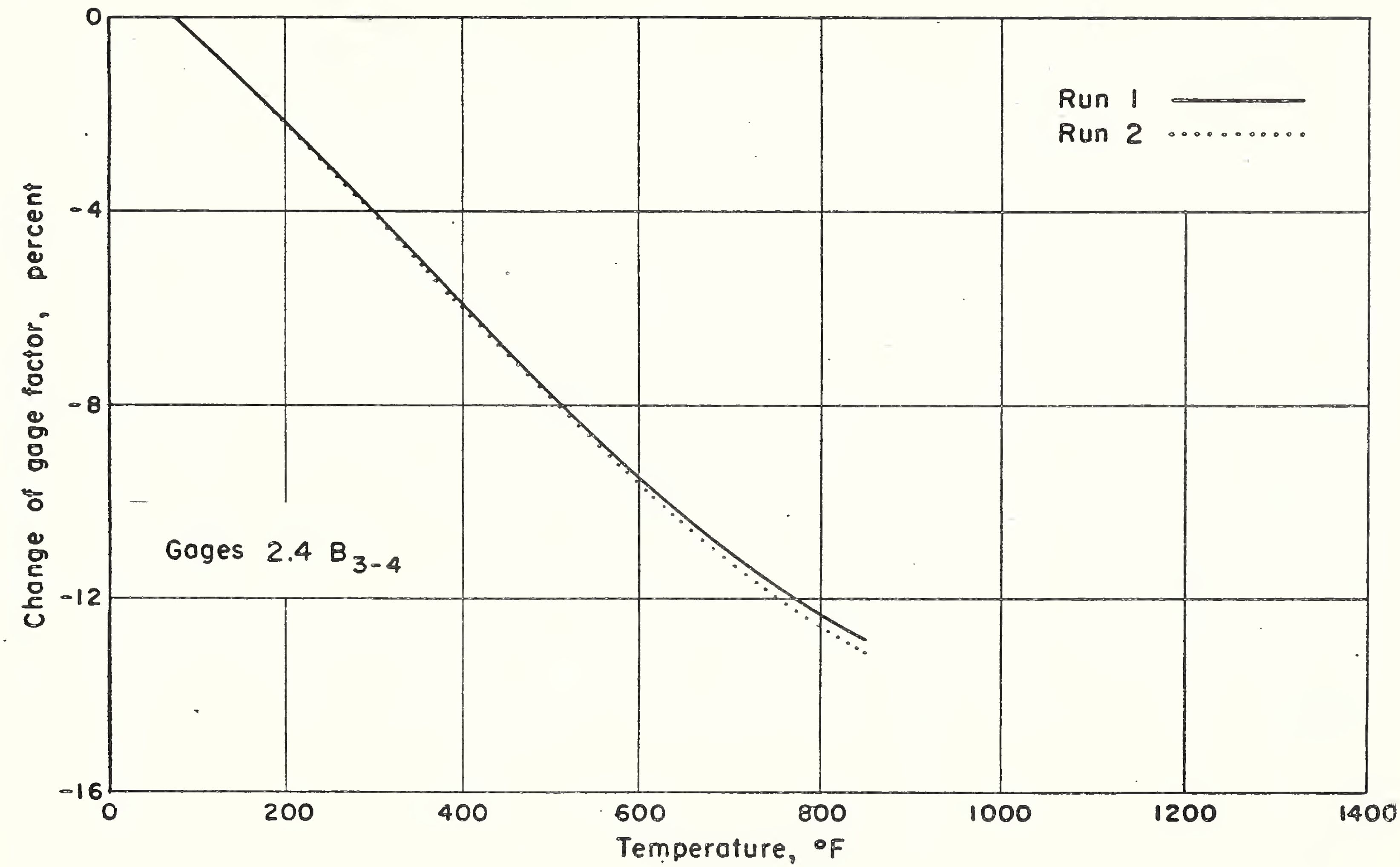


Fig. 8 Variation of gage factor with temperature.

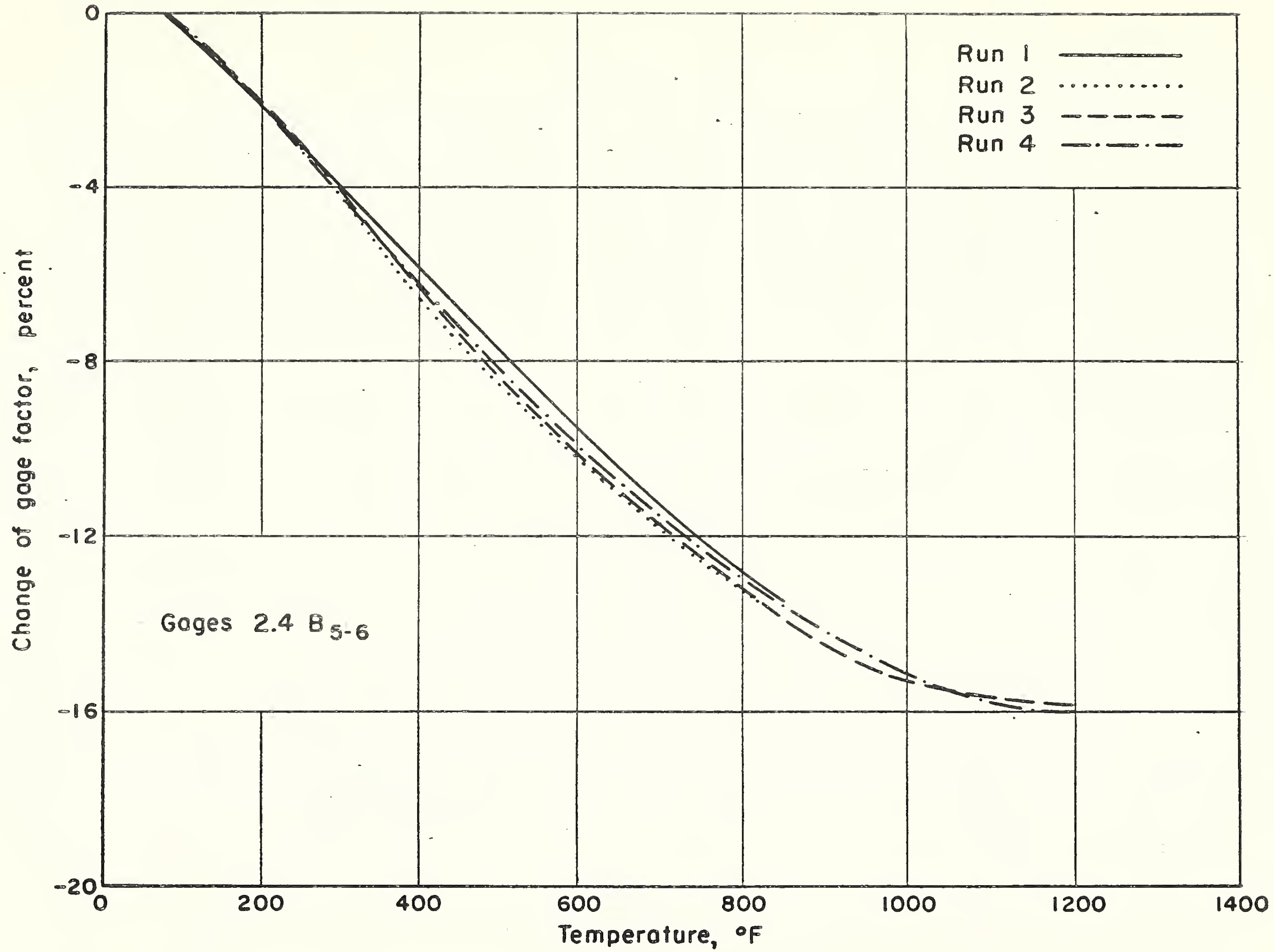


Fig. 9 . Variation of gage factor with temperature.

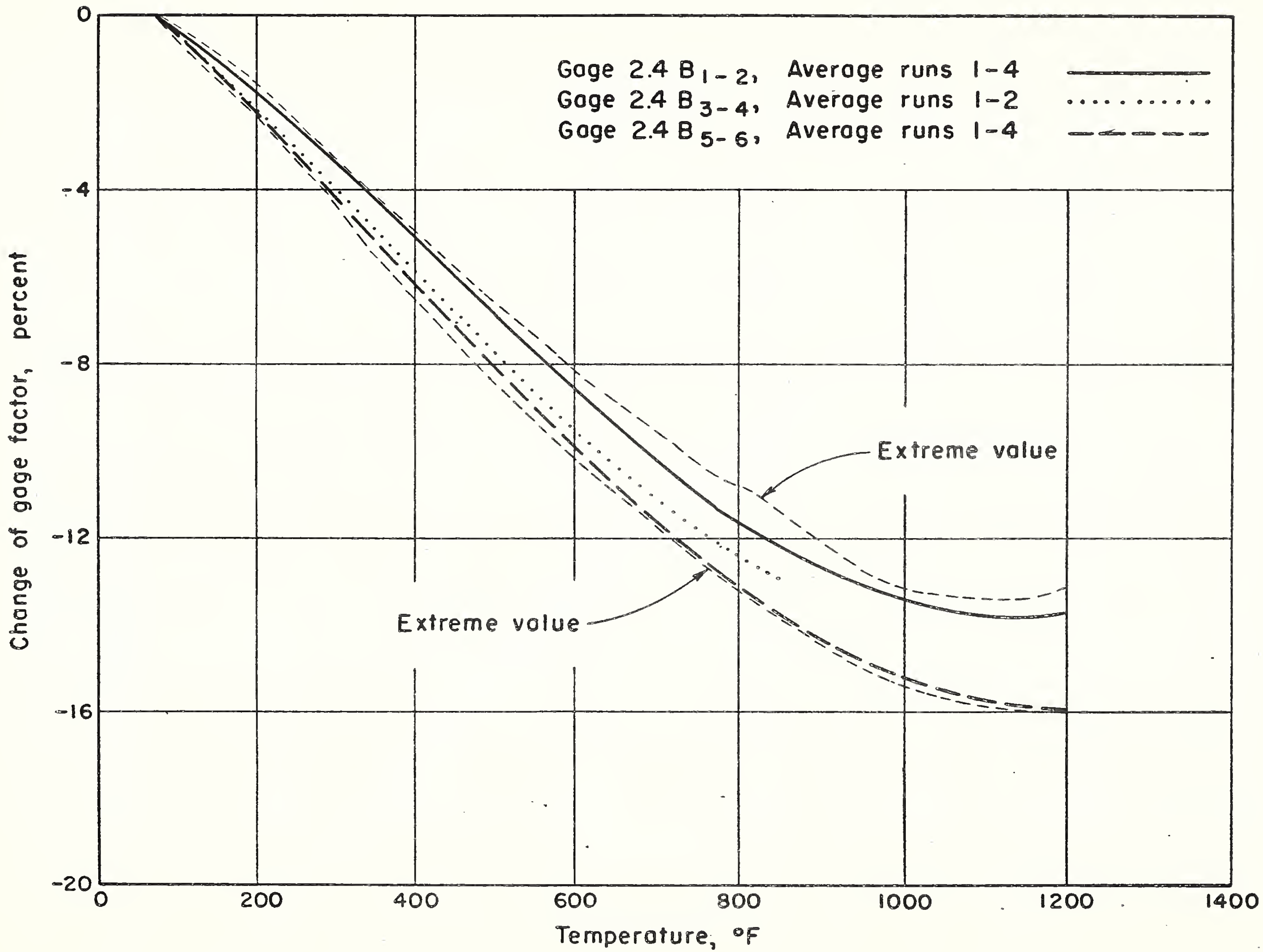


Fig. 10 Variation of gage factor with temperature.

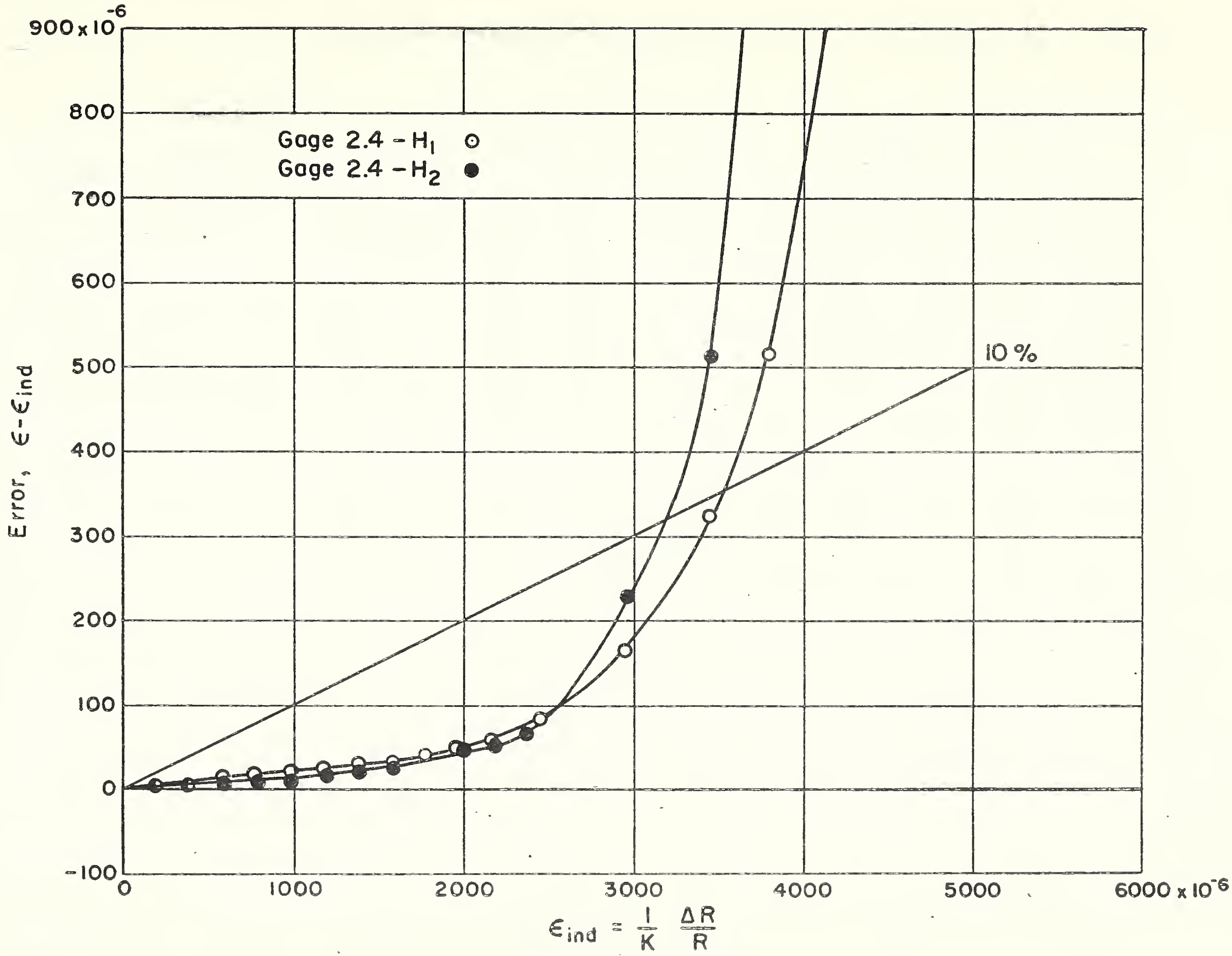


Fig.11 Gage behavior at high strains at 75° F

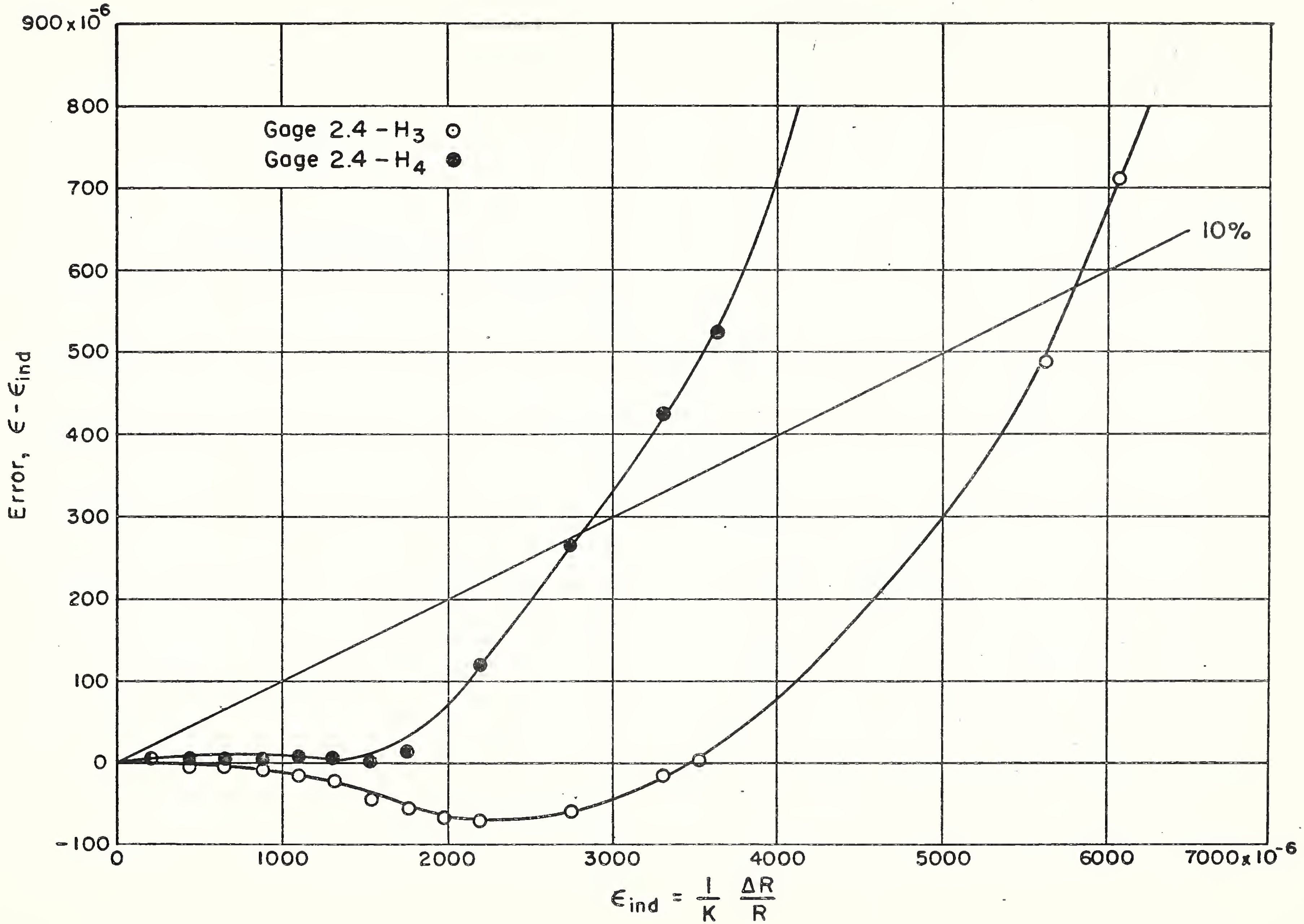


Fig.12 Gage behavior at high strains at 600° F.

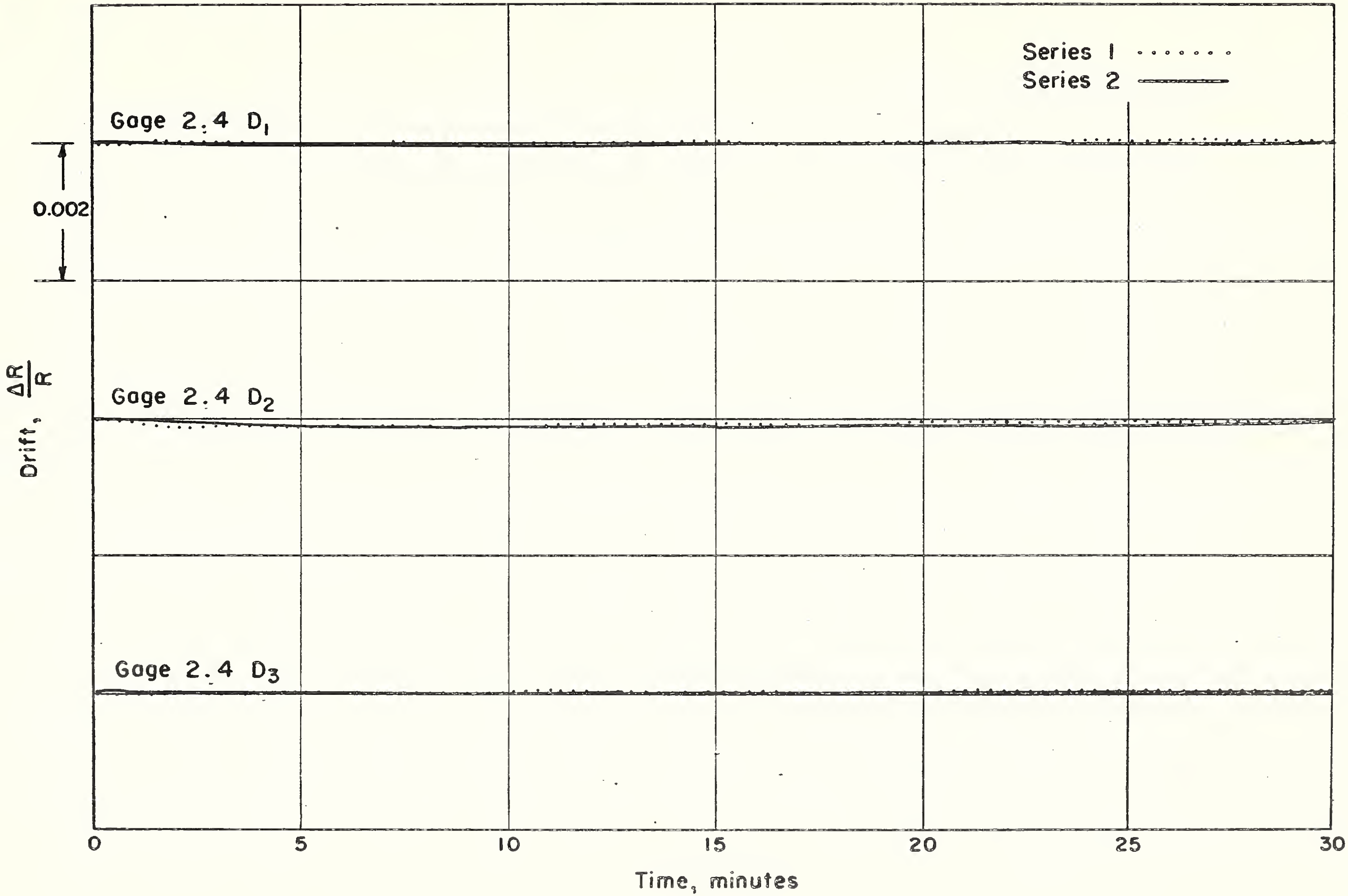


Fig. 13 Drift behavior at 600 °F

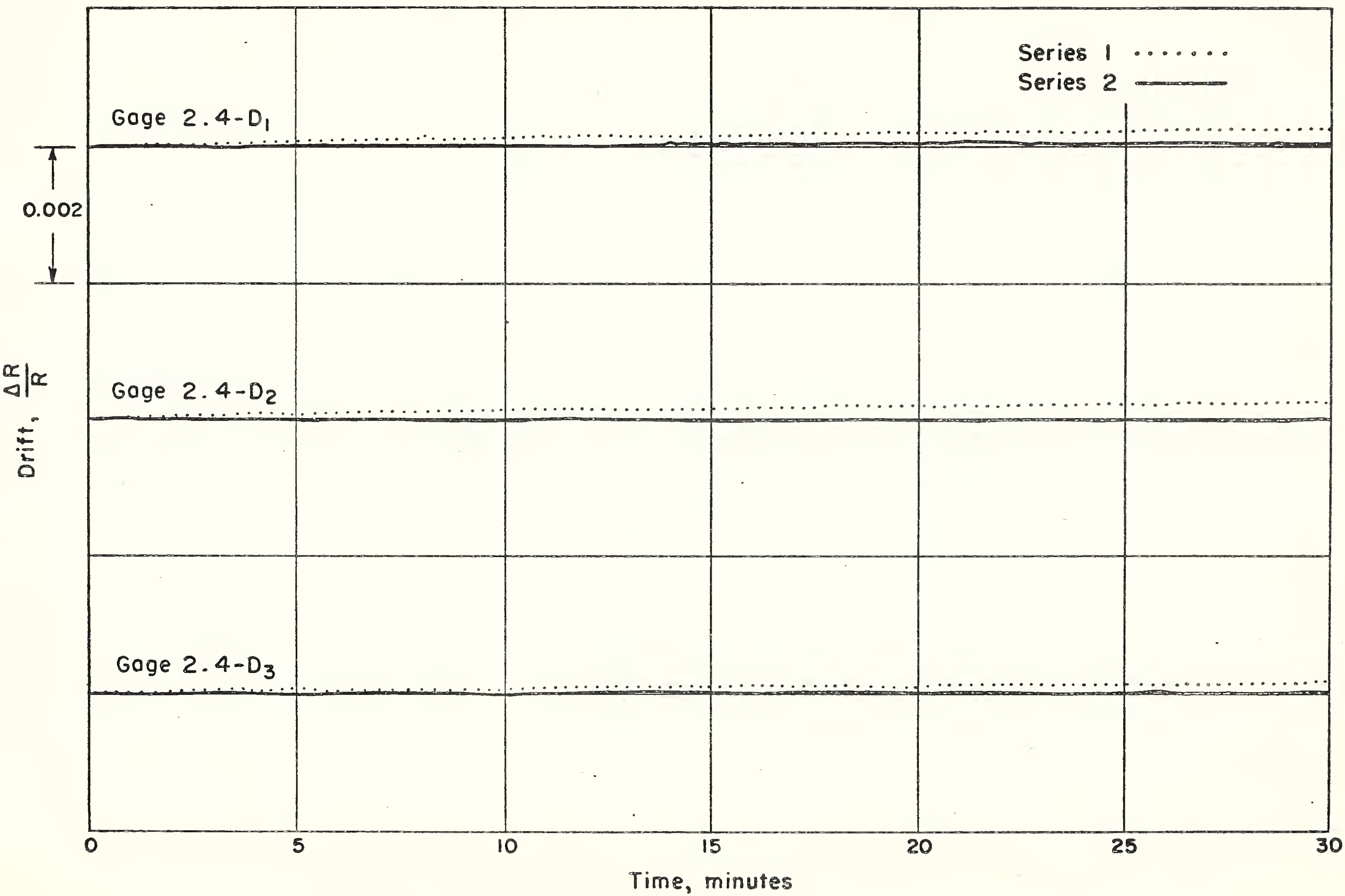


Fig. 14 Drift behavior at 700° F

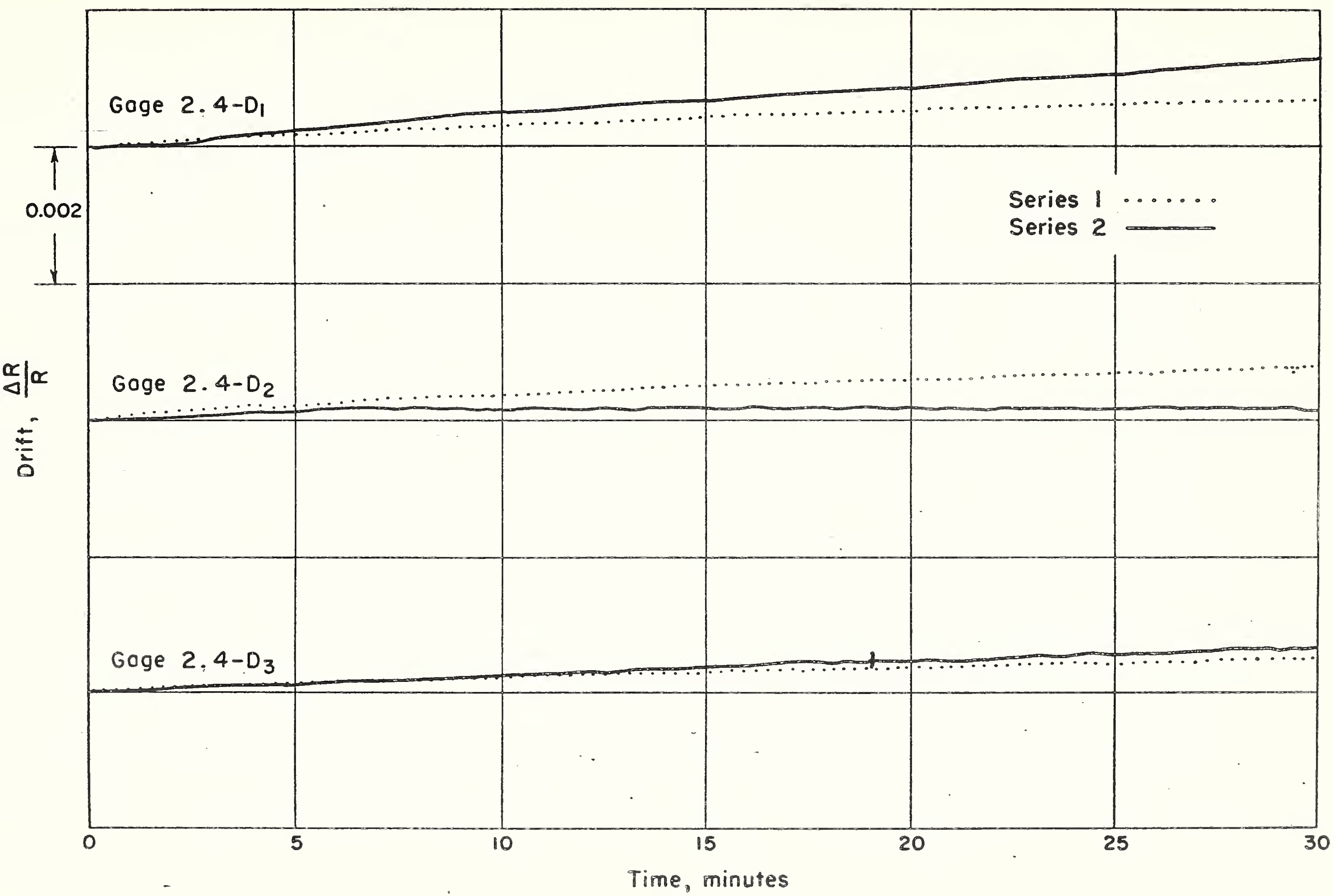


Fig. 15 Drift behavior at 800° F.

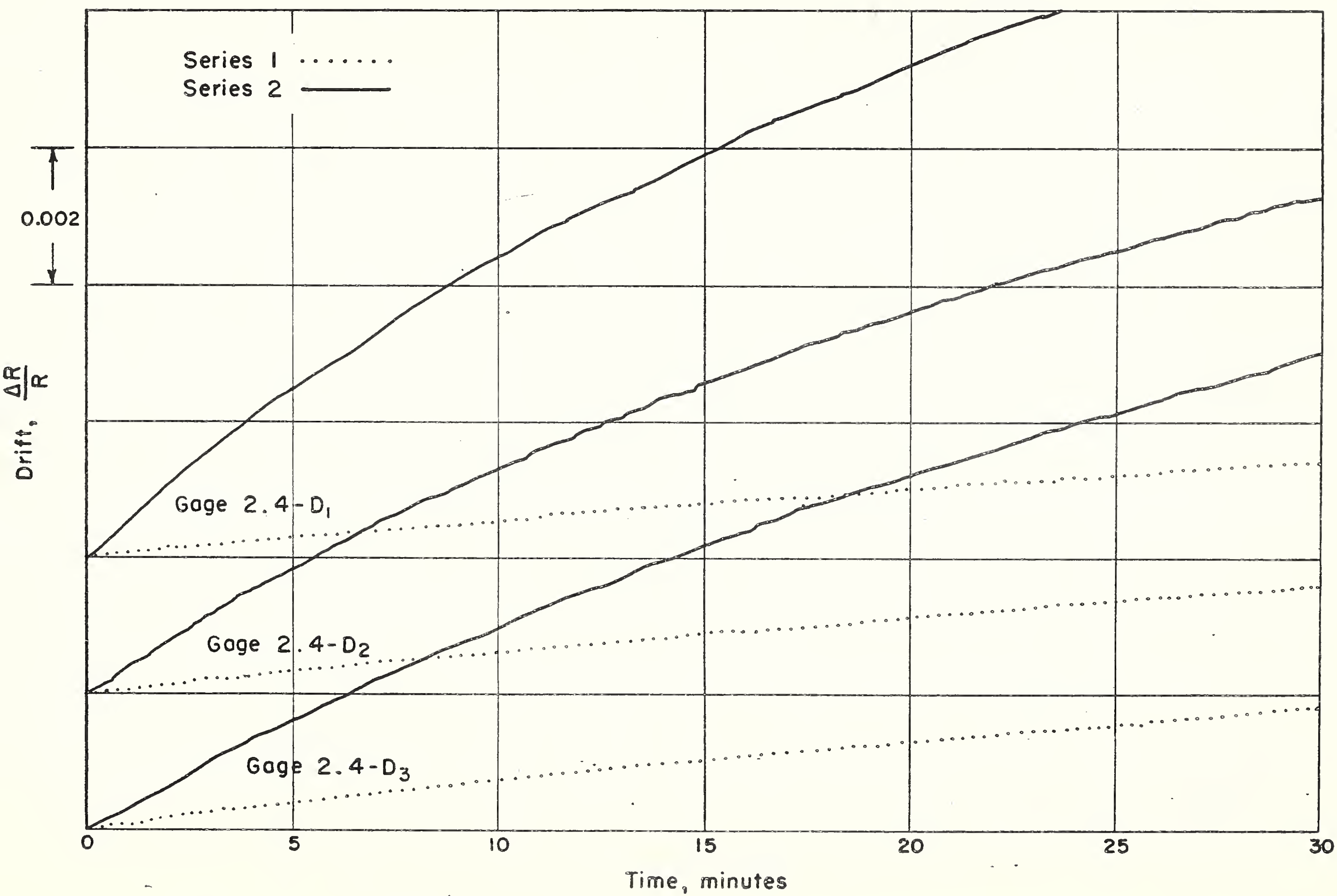


Fig. 16 Drift behavior at 900° F

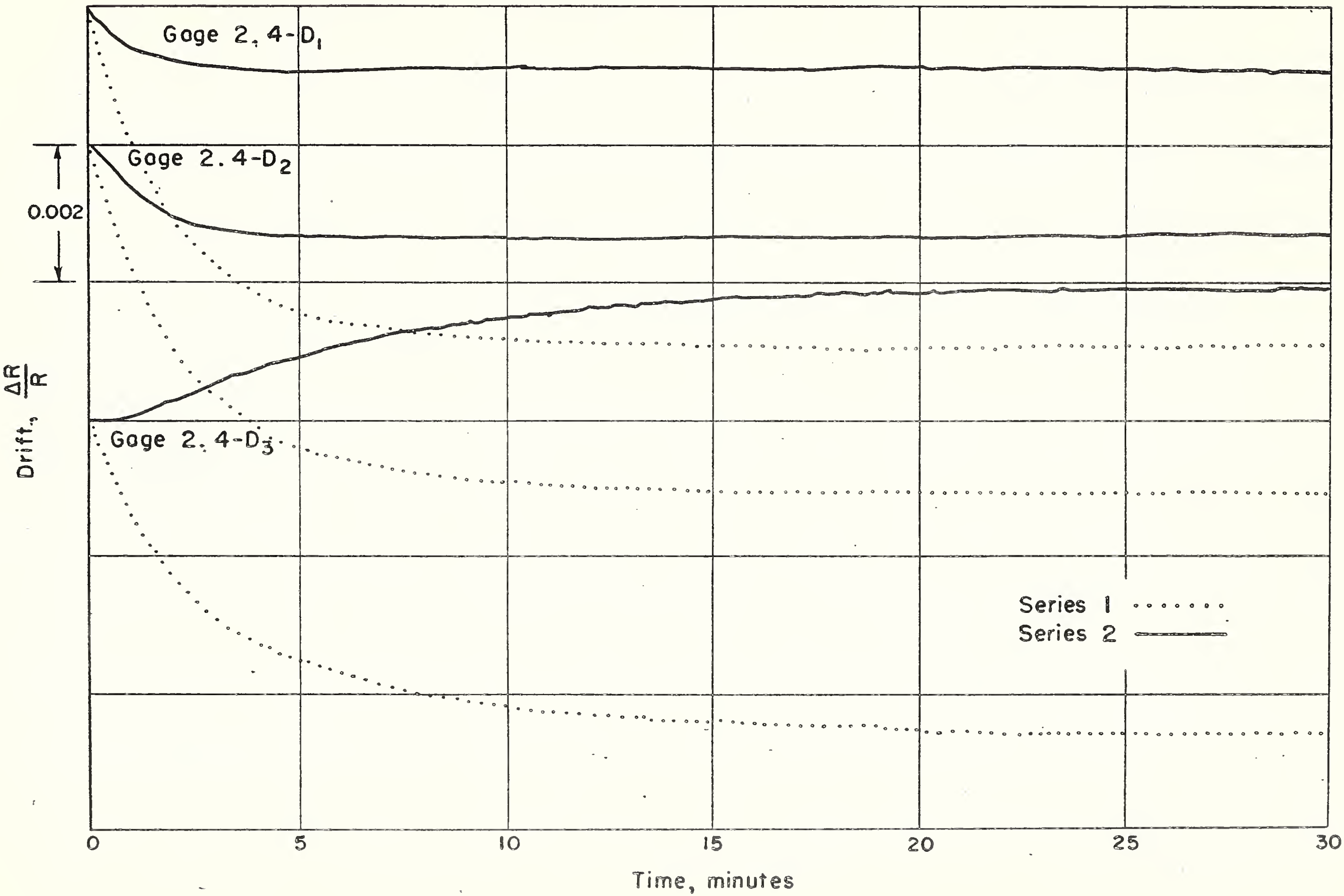


Fig. 17 Drift behavior at 1000° F

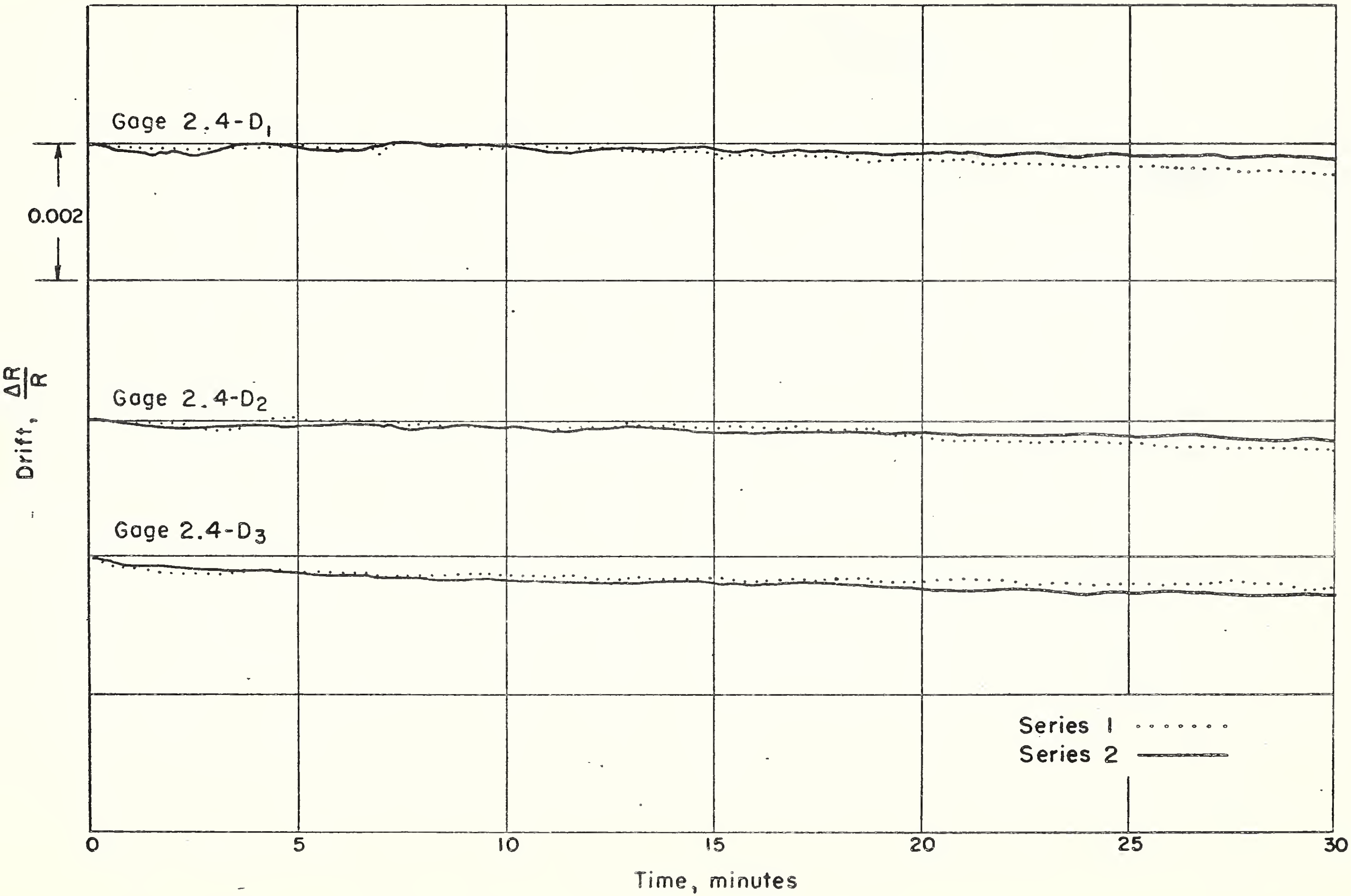


Fig. 18 Drift behavior at 1100° F

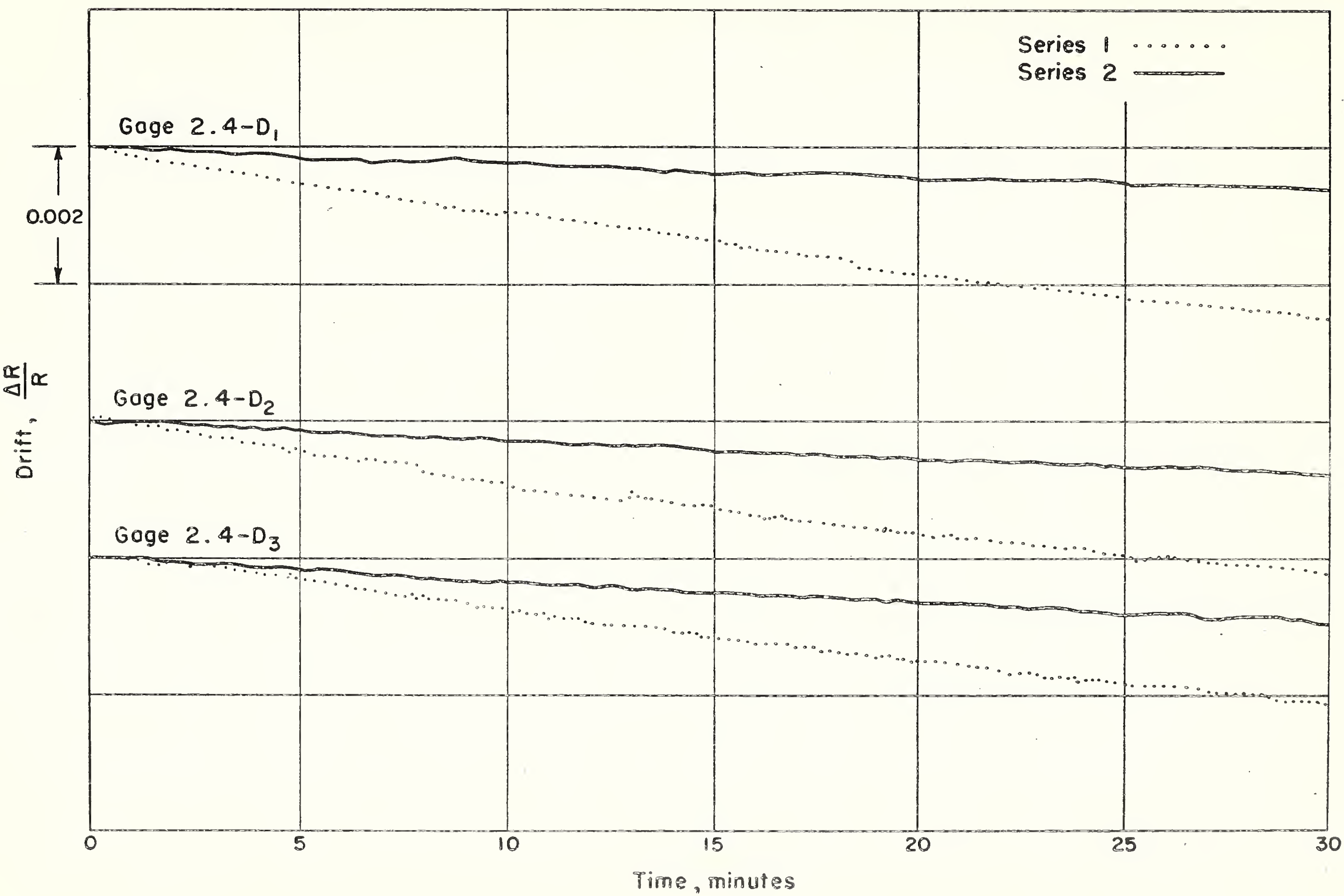


Fig. 19 Drift behavior at 1200°F

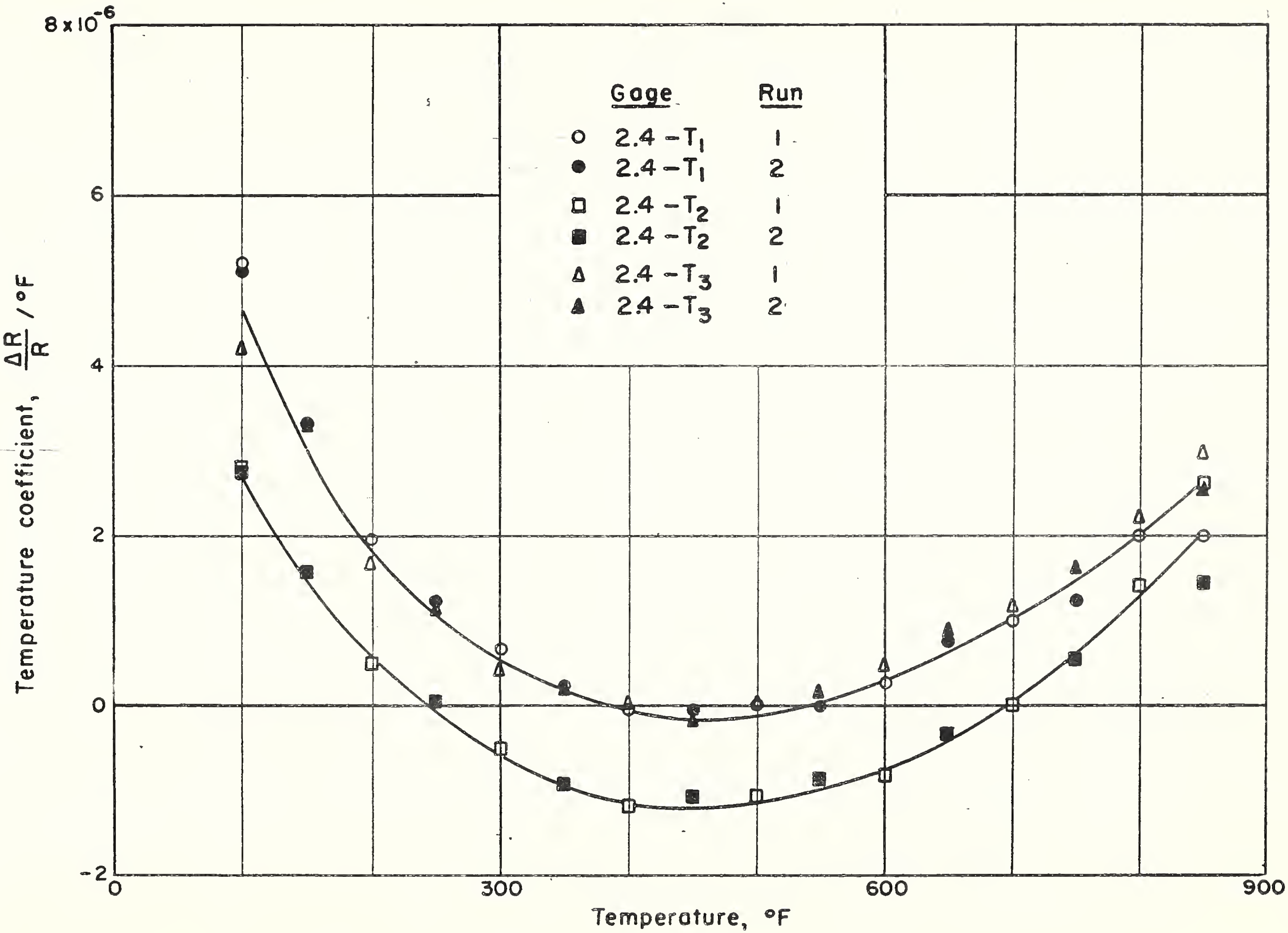


Fig.20 Temperature coefficients to 850° F

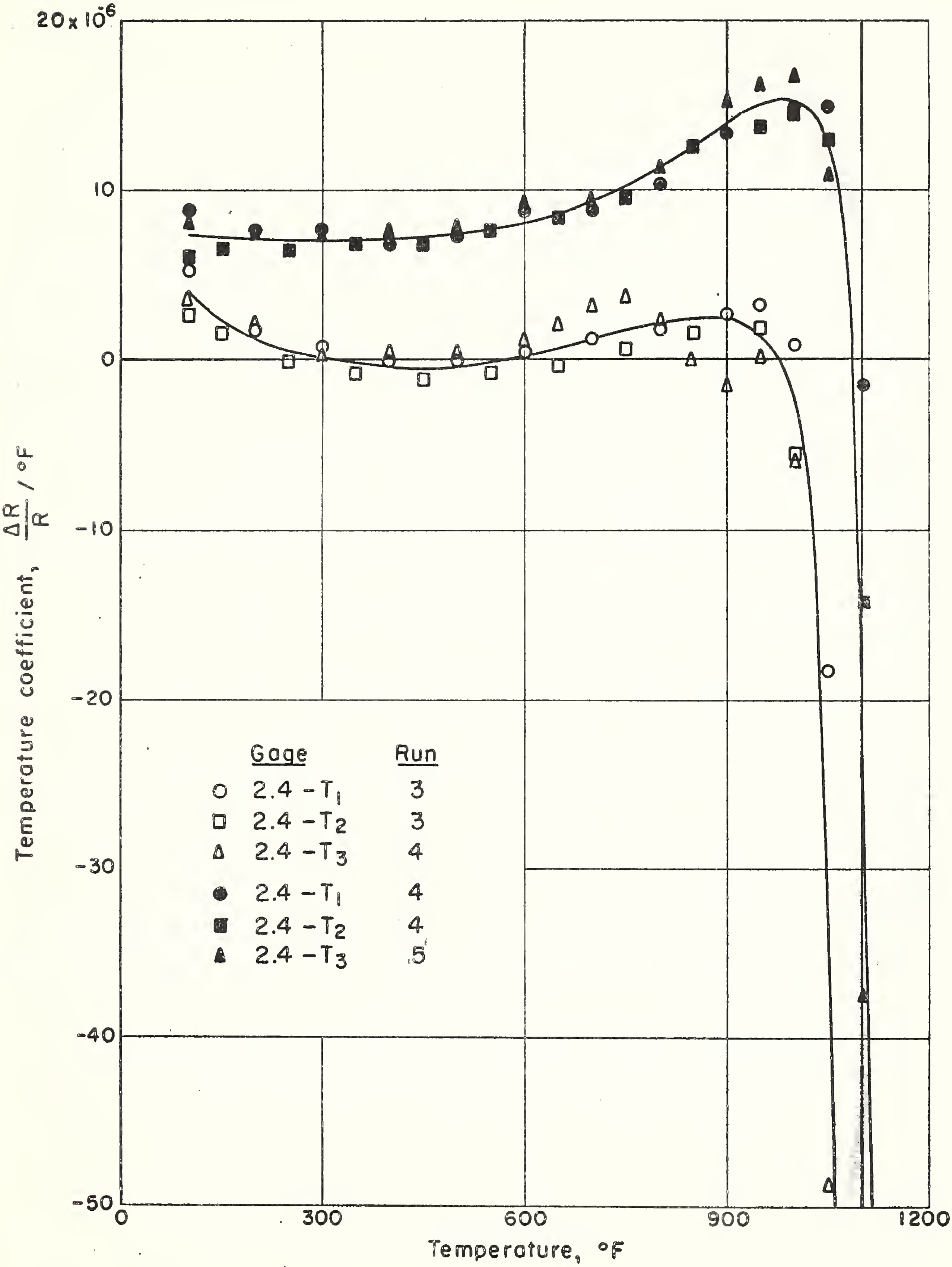


Fig. 21 Temperature coefficients to 1200° F

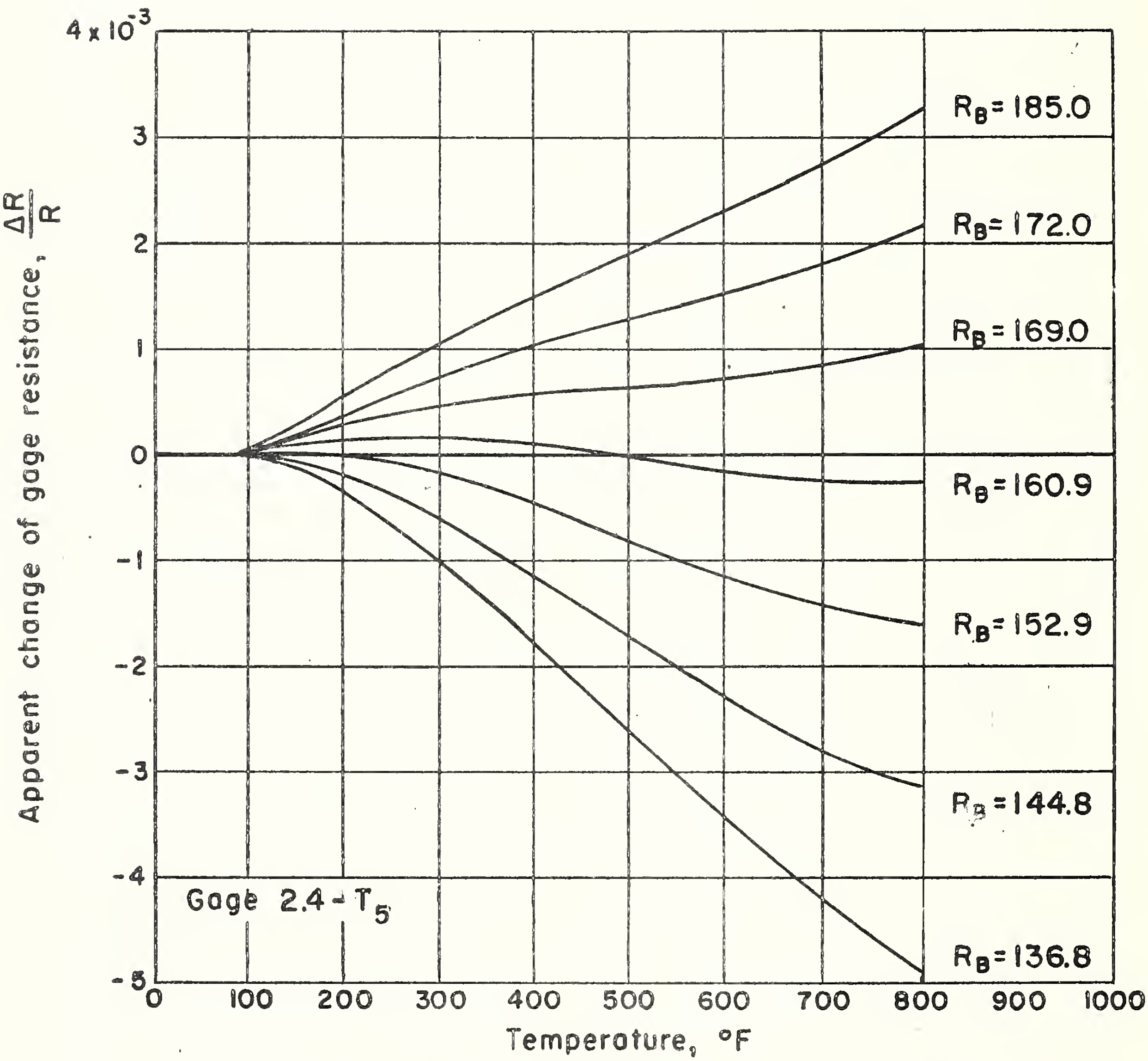


Fig.22 Effect of R_B on the temperature sensitivity of a gage mounted on stainless steel.

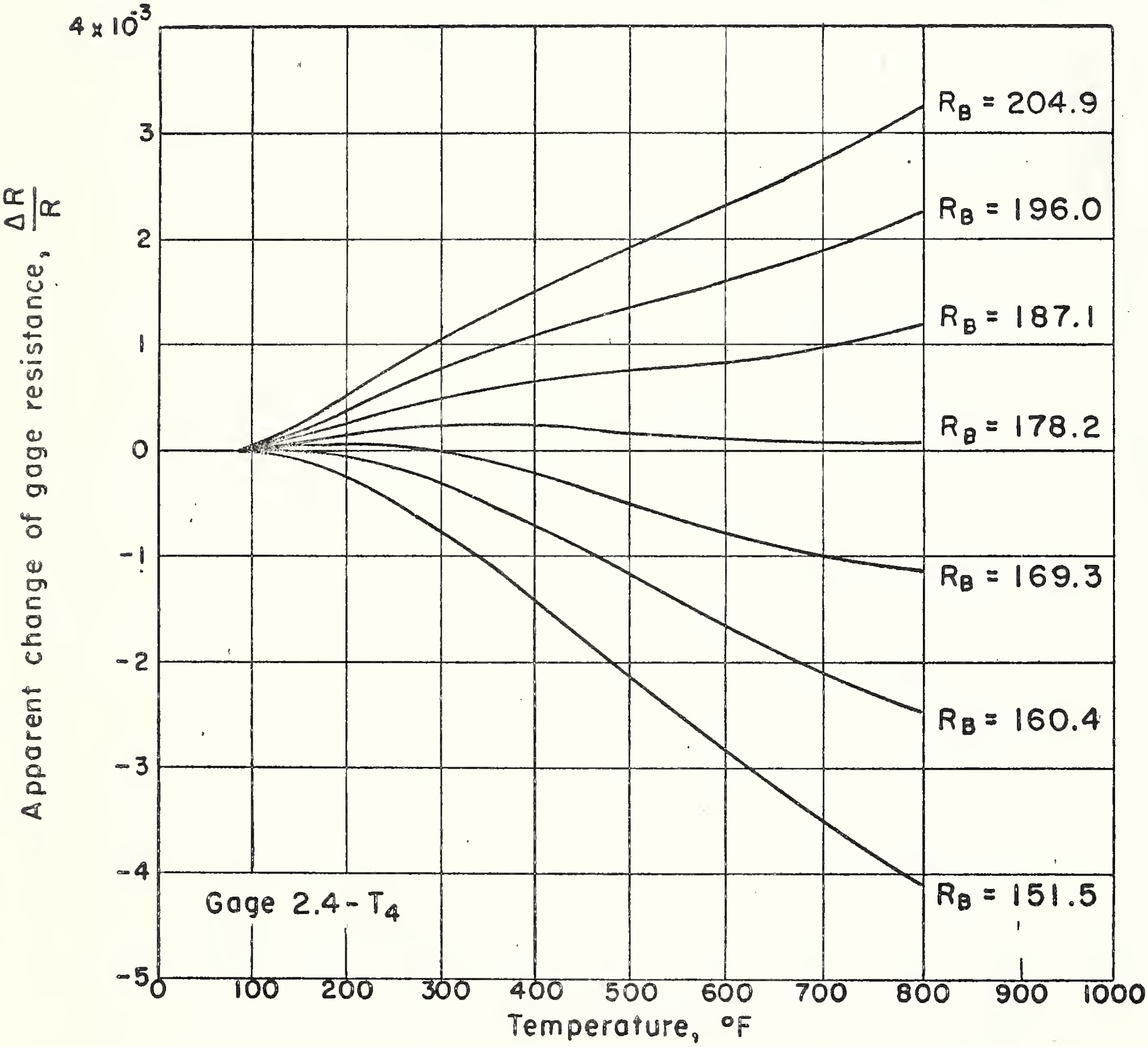


Fig.23 Effect of R_B on the temperature sensitivity of a gage mounted on Inconel.

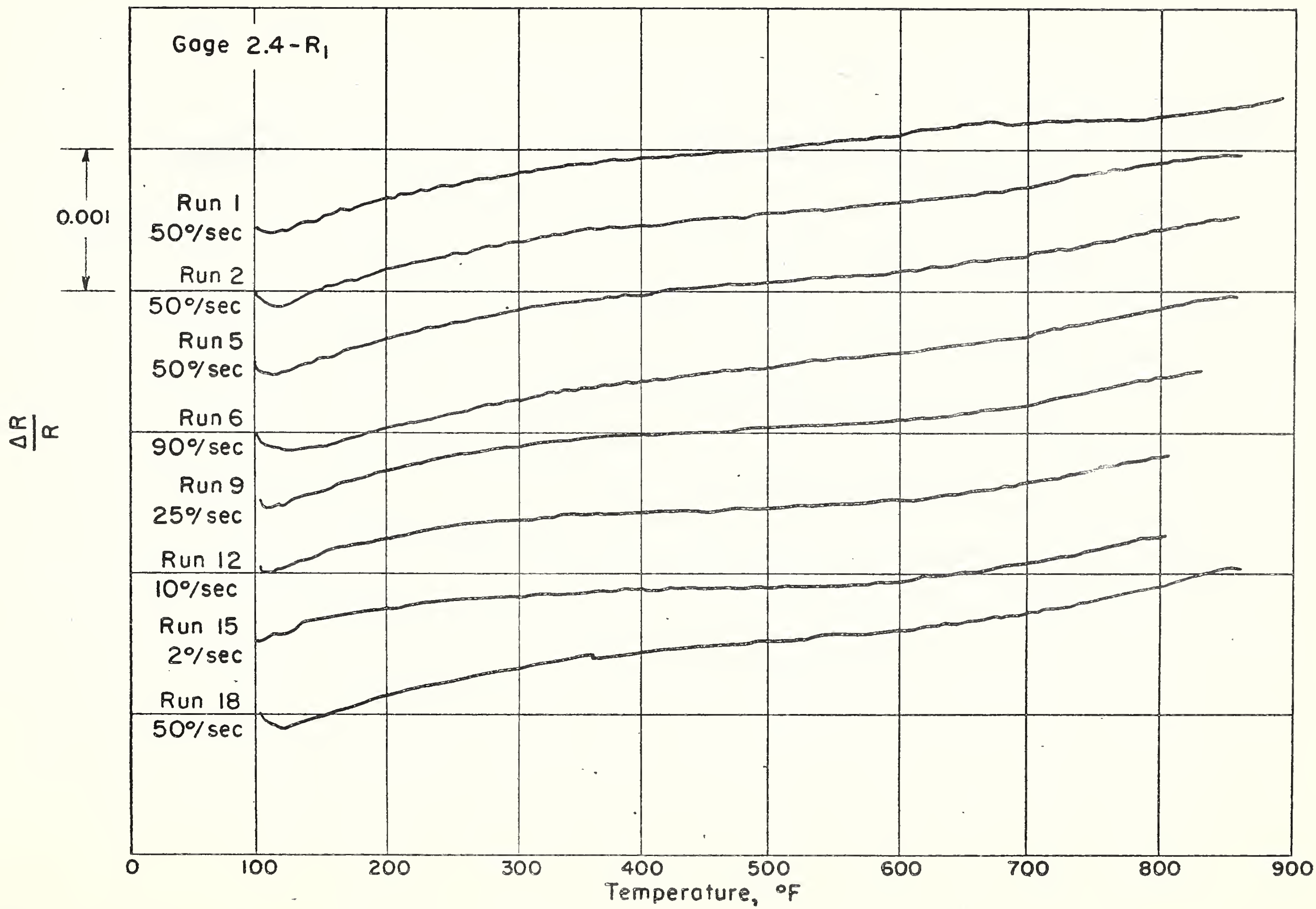


Fig. 24 Variation of gage resistance with increasing temperature at various heating rates.

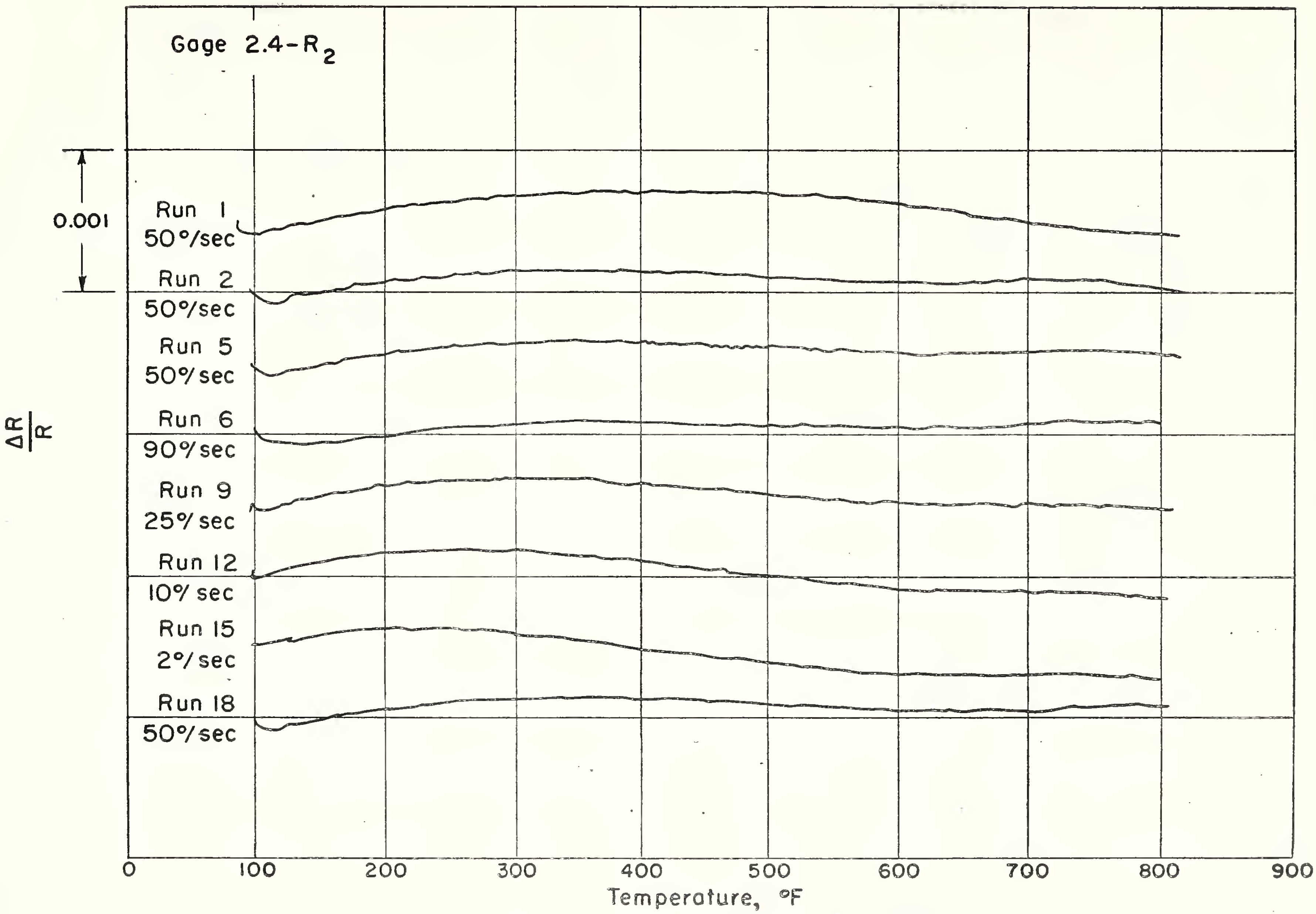


Fig. 25 Variation of gage resistance with increasing temperature at various heating rates.

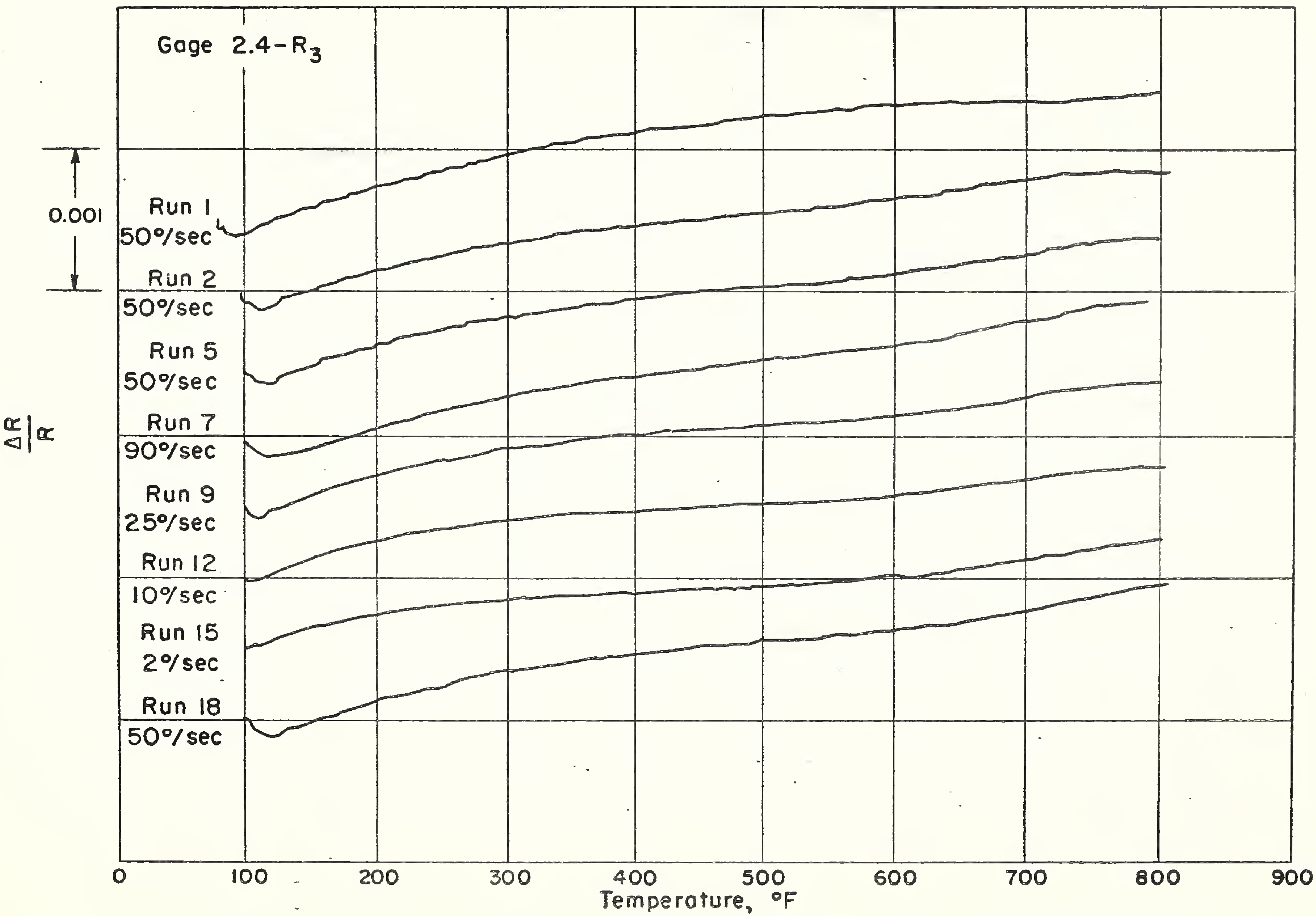


Fig. 26 Variation of gage resistance with increasing temperature at various heating rates.

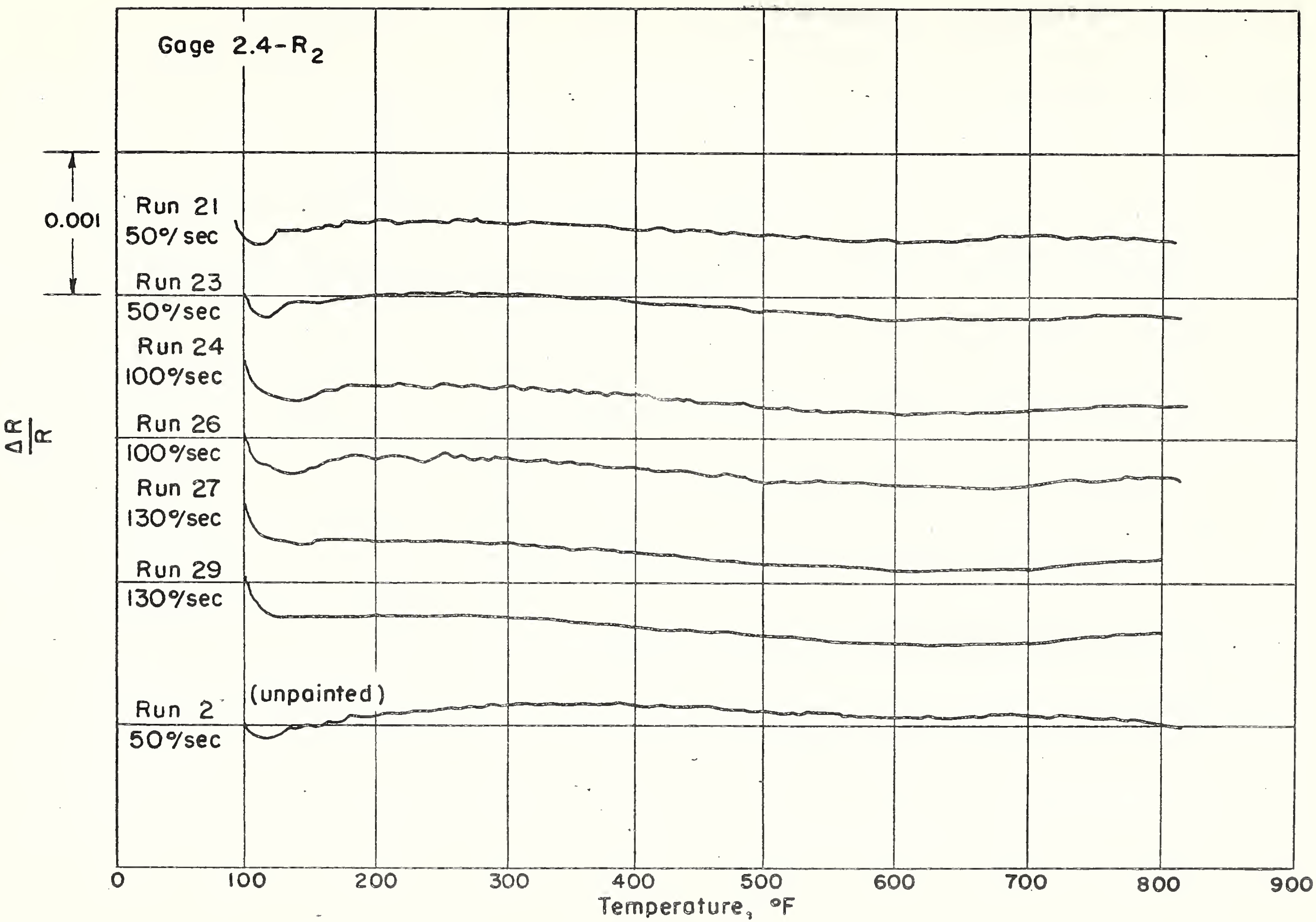


Fig. 27 Variation of gage resistance with increasing temperature at various heating rates. Gaged area painted.

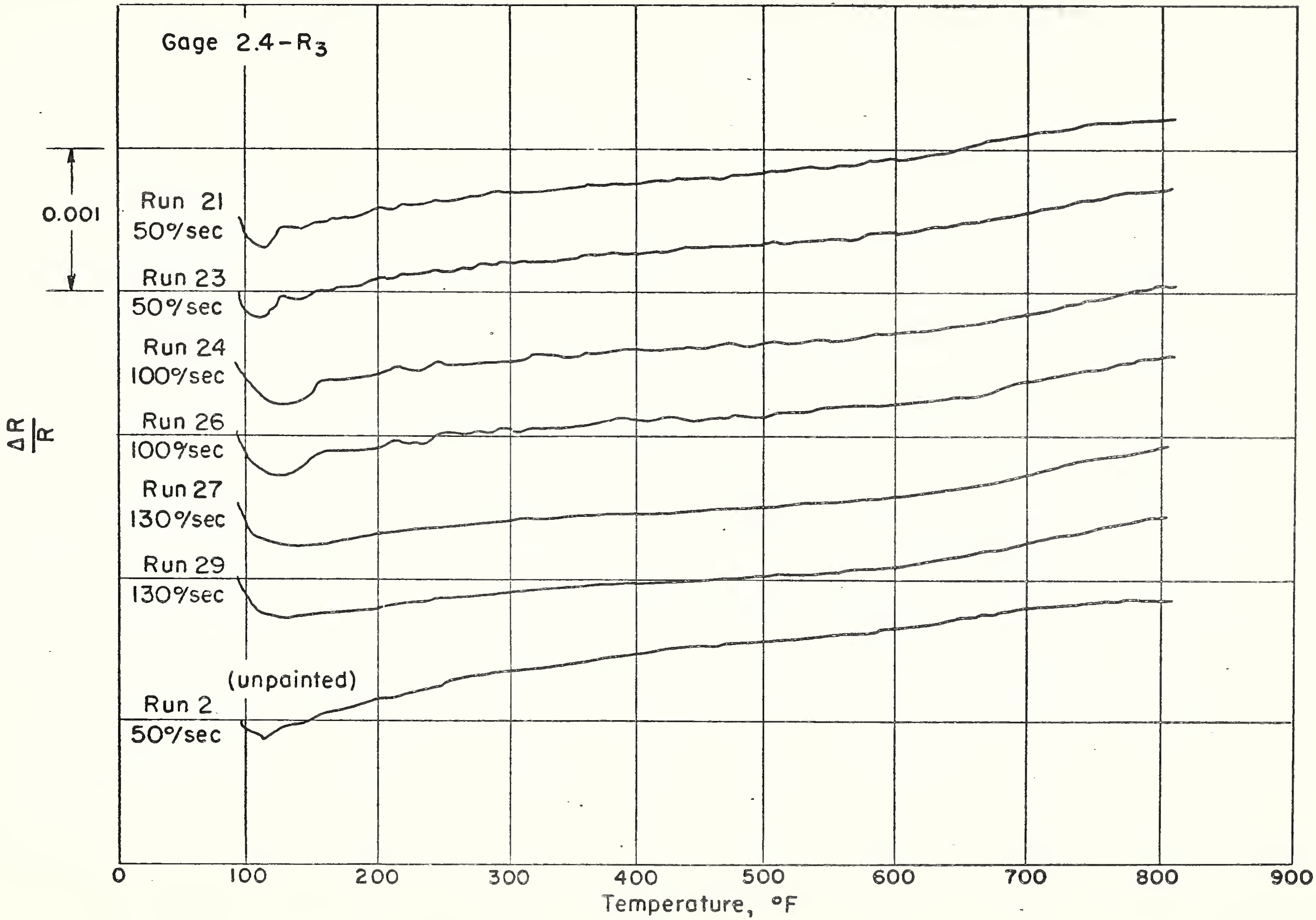


Fig. 28 Variation of gage resistance with increasing temperature at various heating rates. Gaged area painted.

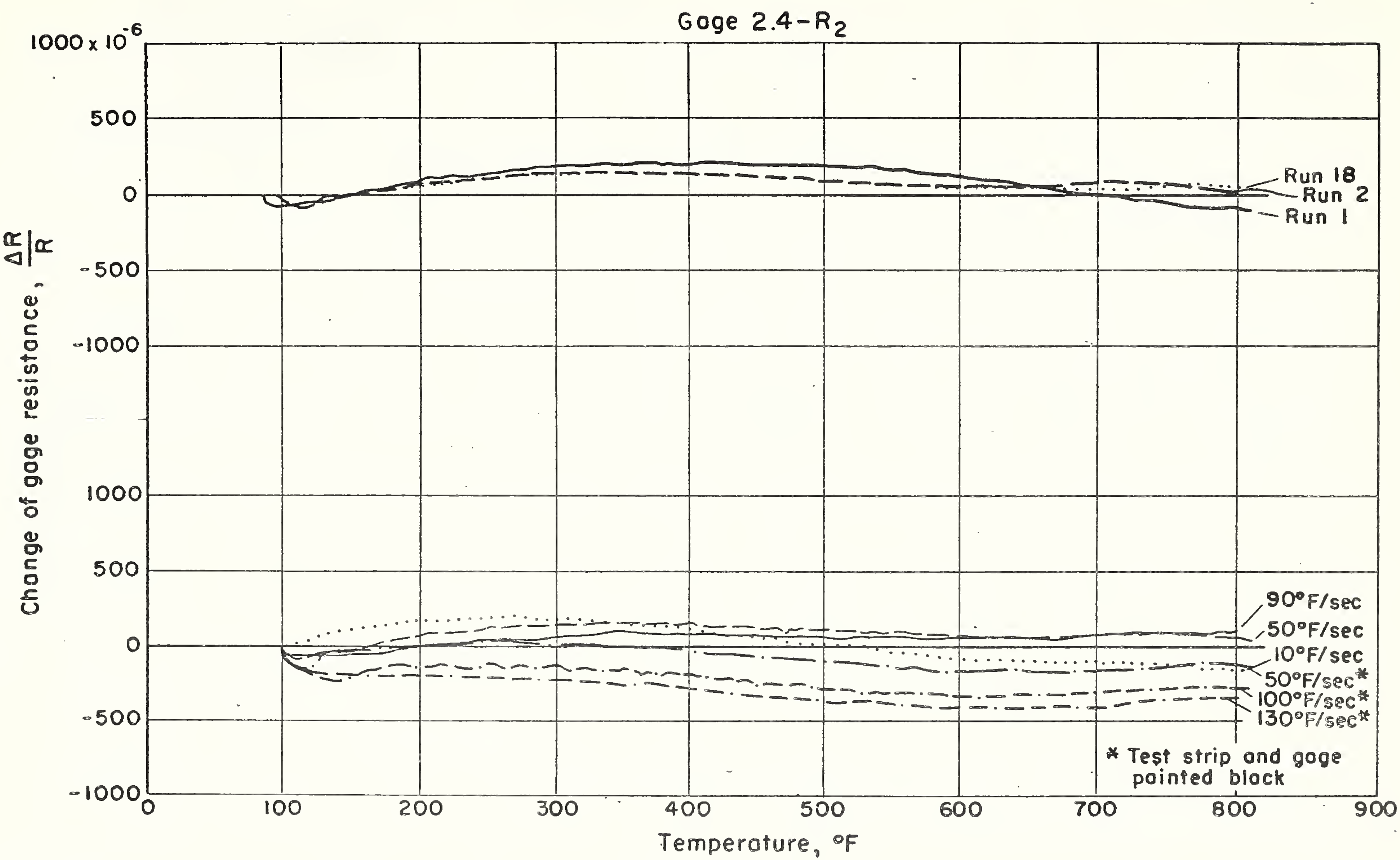


Fig. 29 Effect of heating rate and history on gage response with transient heating.

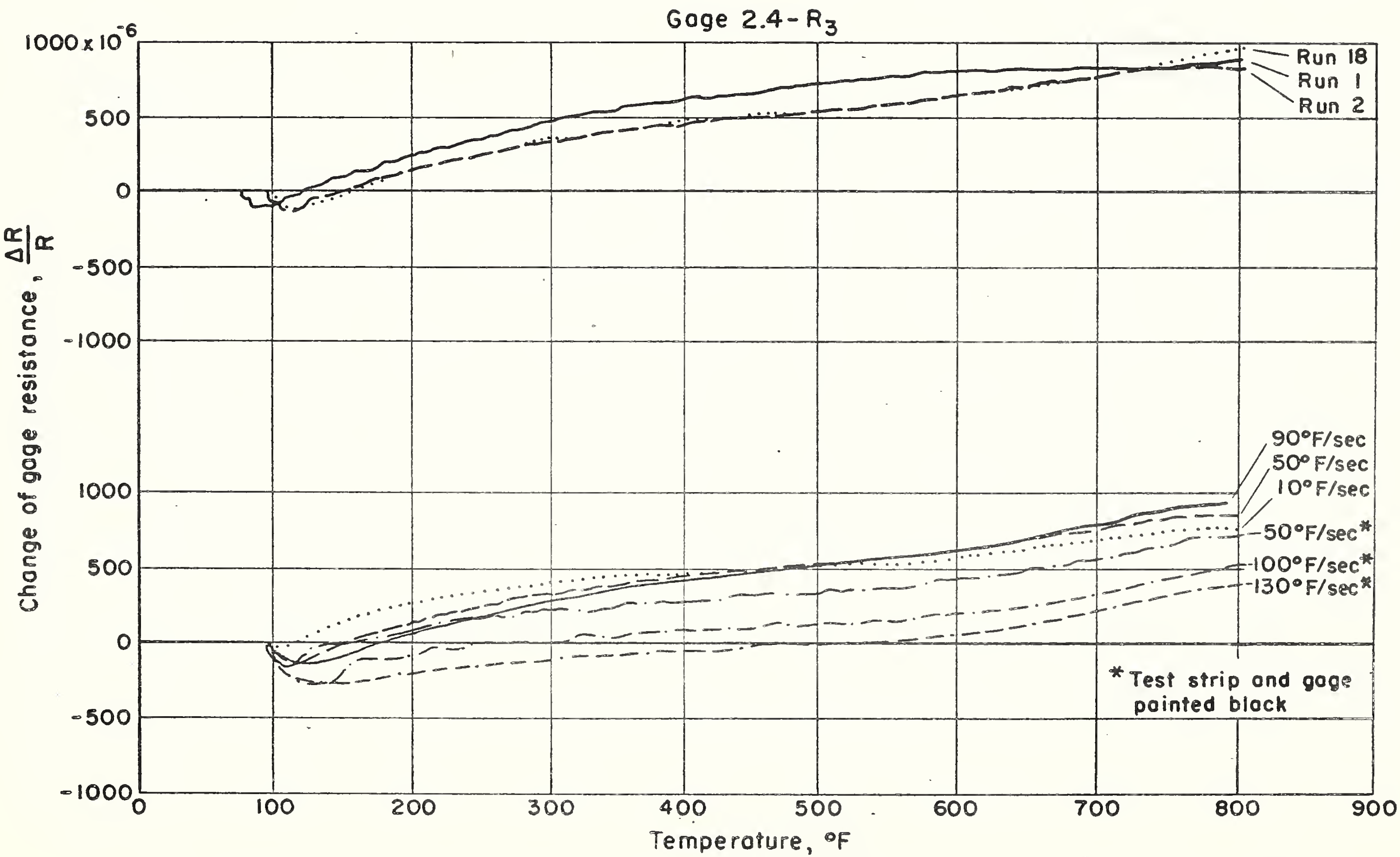


Fig. 30 Effect of heating rate and history on gage response with transient heating.

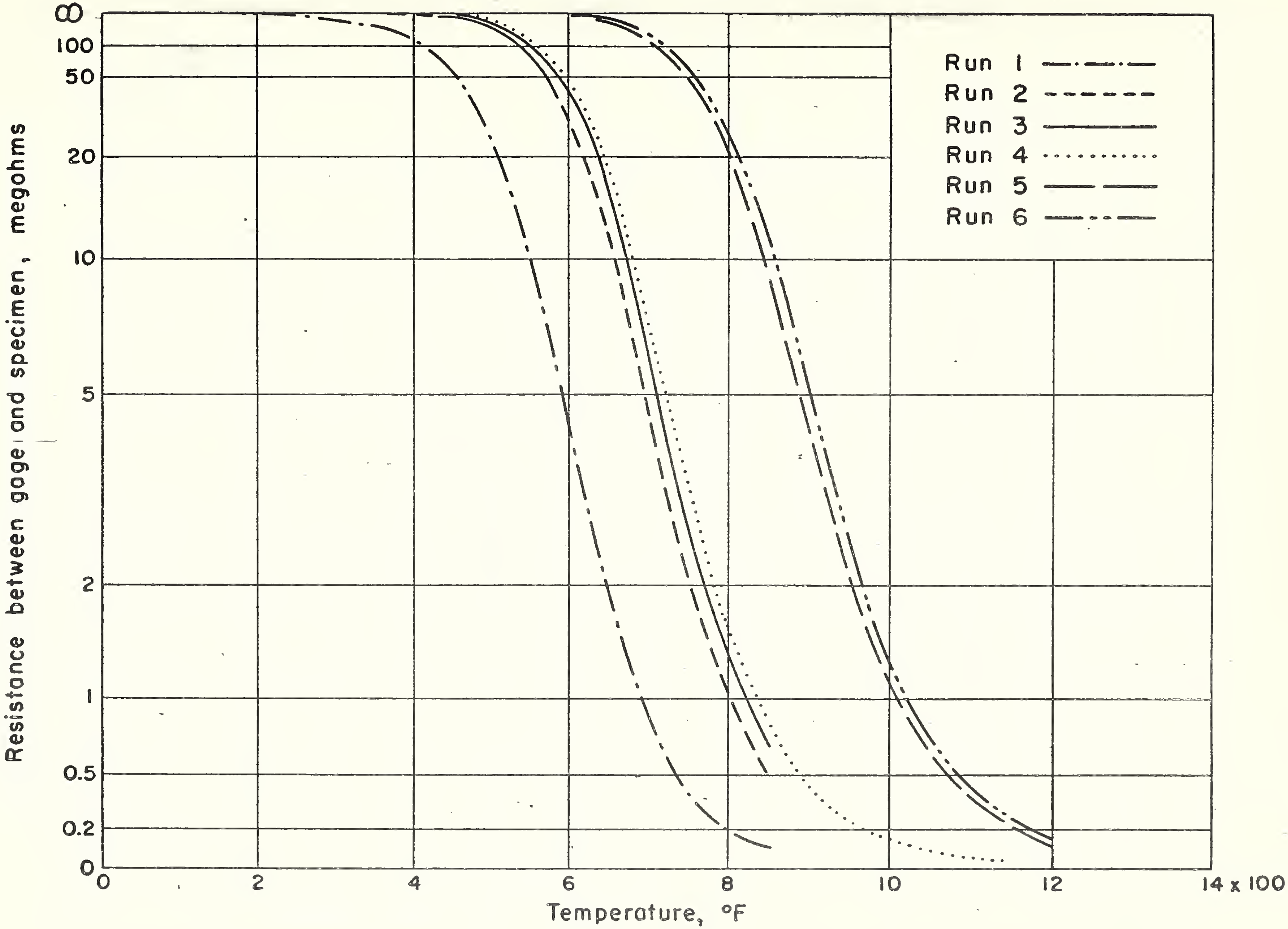


Fig.31 Resistance between gage and specimen, Gage No. 2.4-L_1

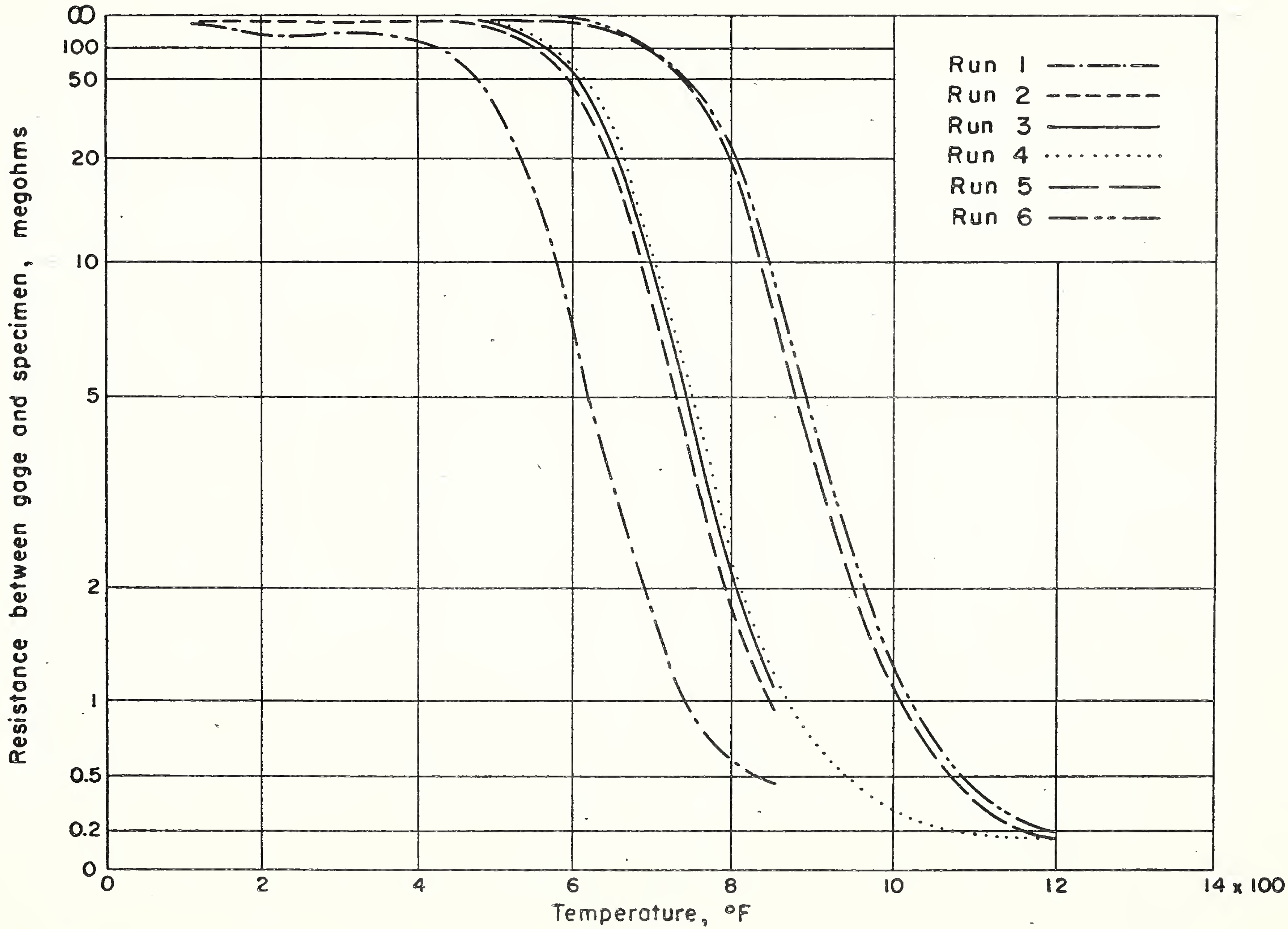


Fig. 32 Resistance between gage and specimen, Gage 2.4-L_2

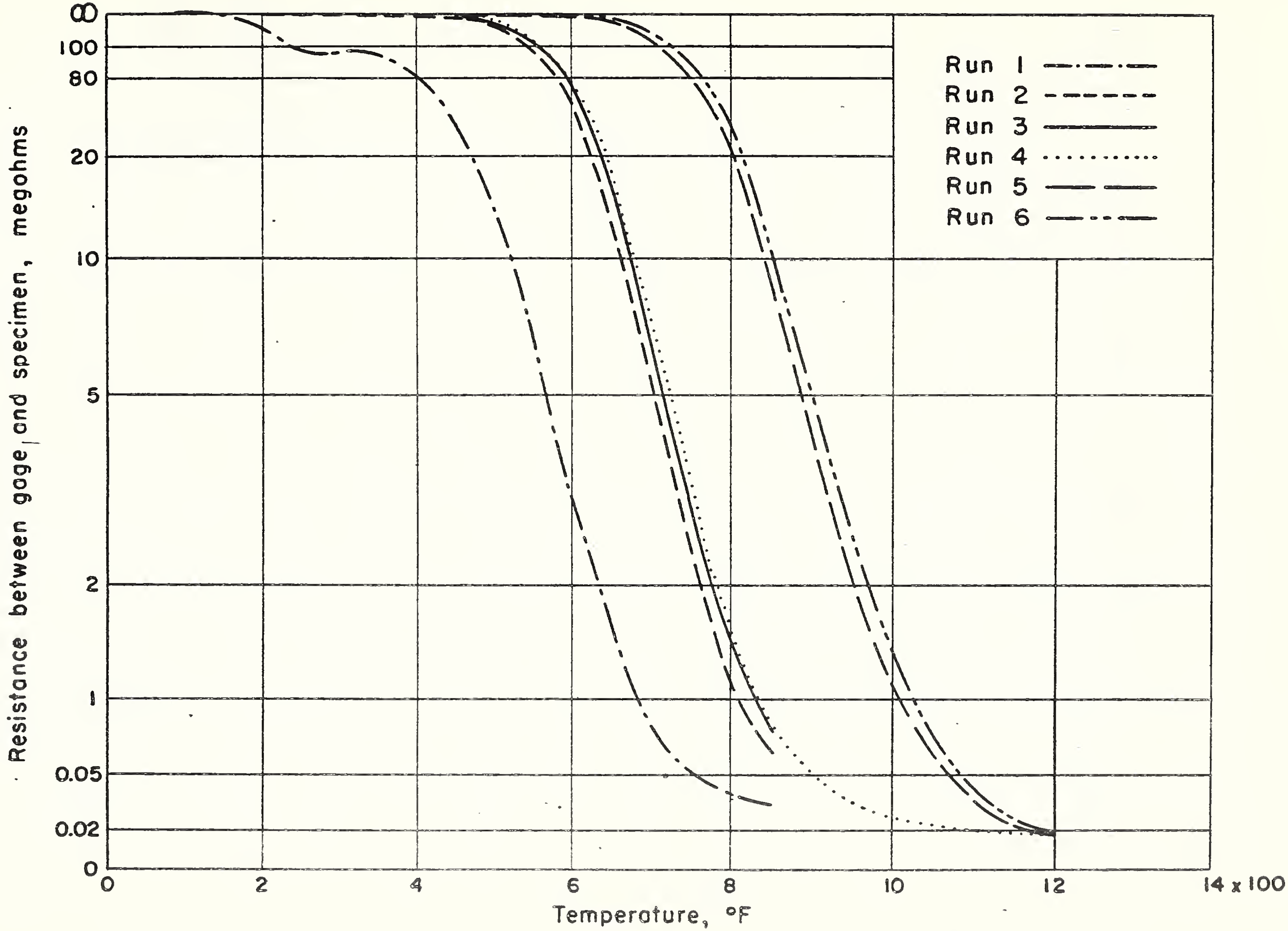


Fig. 33 Resistance between gage and specimen, Gage No. 2.4–L_3

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